RF/MICROWAVE CRITERIA DOCUMENT
FINAL DIRECTOR'S DRAFT
VOLUME I: CHAPTER I-IV

Final Director's Draft

DISCLAIMER

Use of manufacturers' names and equipment model numbers in no way implies an endorsement by the National Institute for Occupational Safety and Health.

PREFACE

The Occupational Safety and Health Act of 1970 emphasizes the need for standards to protect the health and provide for the safety of workers exposed to an ever-increasing number of potential hazards. The National Institute for Occupational Safety and Health (NIOSH) evaluates all available research data, establishes criteria, and recommends standards for occupational exposure. The Secretary of Labor will weigh these recommendations along with other considerations, such as feasibility and means of implementation, in promulgating regulatory standards.

After reviewing data and consulting with others, NIOSH formalized a system for the development of criteria on which standards can be established to protect the health and to provide for the safety of workers. The criteria and recommended standard should enable management and labor to develop better engineering controls and more healthful work environments, and simple compliance with the recommended standard should not be the final goal.

NIOSH will periodically review the recommended standards to ensure continuing protection of workers and will make successive reports as new information becomes available.

The contributions to this document on radiofrequency and microwave radiation by NIOSH staff, other Federal agencies or departments, professional societies, trade associations, public interest groups, and the review consultants are gratefully acknowledged.

The views expressed and conclusions reached in this document, together with the recommendations for a standard, are those of NIOSH. They are not necessarily those of the consultants, the reviewers selected by, or representing, organized labor, professional societies, trade associations, environmental and public interest groups, or Federal or state agencies. However, all comments, whether or not incorporated, have been sent with the criteria document to the Occupational Safety and Health Administration (OSHA) for its consideration in setting the standard. The review consultants, Federal agencies, and professional societies and trade associations that received the document for review appear on pages vi-xi.

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SYNOPSIS

This report reviews available scientific and technical information on radiofrequency and microwave radiation, and it recommends a standard for the control of radiofrequency and microwave radiation hazards in the workplace. The standard is designed to protect workers from potential hazards resulting from thermal heating or from possible "nonthermal" bioeffects reported in the literature.

In the United States, estimates of the number of workers exposed to radiofrequency and microwave radiation have been as high as 21 million. Radiofrequency and microwave radiation is used in broadcasting, communications, food processing and cooking, sealing and laminating, drying, medical diathermy, therapeutic hyperthermia, and radar, among other uses.

The standard recommended to the US Department of Labor consists of a workplace (environmental) limit that is dependent on electromagnetic frequency. This limit is defined in terms of mean squared electric (E) and magnetic (H) field strengths. Plane-wave equivalent power densities are also given, but measurement of power density alone is not sufficient for compliance with the recommended standard at certain frequencies. Recommendations are also included for medical surveillance, labeling and posting, work practices, engineering controls, monitoring and recordkeeping, informing employees of hazards, and training.

Further research is needed in the following areas: (1) long-term studies of the effects of low-level radiofrequency and microwave radiation on animals, with particular attention paid to measurements of incident electric and magnetic field strengths and absorbed dose; (2) determination of any irreversible changes induced by exposure to radiofrequency and microwave radiation; (3) studies of the mechanisms of interaction between radiofrequency and microwave radiation and the whole body, specific organs, tissues, and cells; (4) comprehensive long-term epidemiologic investigations of exposed populations using well-characterized study and control groups; (5) further studies of human whole-body and partial-body absorption characteristics with respect to radiofrequency and microwave energy; and (6) the importance of pulsing variables in the production of biologic effects by pulsed radiofrequency and microwave radiation.

The Division of Criteria Documentation and Standards Development, National Institute for Occupational Safety and Health (NIOSH), had primary responsibility for development of the criteria and recommended standard for radiofrequency and microwave radiation. Zorach (Zory) R. Glaser, Ph.D., of this Division served as the criteria manager. Equitable Environmental Health, Inc. (EEH) developed the basic information for consideration by NIOSH staff and consultants under contract CDC 210-78-0112.

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American Conference of Governmental Industrial Hygienists

American Industrial Hygiene Association

American National Standards Institute
Subcommittee C95.4

Association of Home Appliance Manufacturers

Bioelectromagnetics Society

Electronic Industries Association

Institute of Electrical and Electronic Engineers
Committee on Man and Radiation

International Microwave Power Institute

National Forest Products Association

Natural Resources Defense Council

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I. RECOMMENDATIONS FOR A RADIOFREQUENCY AND MICROWAVE STANDARD

NIOSH recommends that employee exposure to radiofrequency (RF) and microwave energy in the frequency range of 300 kilohertz (kHz) - 300 gigahertz (GHz) or 0.3-300,000 megahertz (MHz) be controlled by adherence to the following sections (see Chapters II and XII for a further description of terms). The recommended standard is designed to protect the health and provide for the safety of employees for up to a 10-hour workshift, in a 40-hour workweek, over a working lifetime. Compliance with all sections of the recommended standard should prevent adverse effects of exposure to RF and microwave radiation on the health of employees and provide for their safety. Monitoring techniques described in the standard are generally available. NIOSH expects that RF/microwave monitoring instrumentation will become commercially available in the near future that will enable compliance with all portions of the recommended standard (see Chapters V and XI for details on commercially available instrumentation). Although NIOSH considers the recommended workplace limits to be safe levels based on present information, employers should regard them as the upper boundaries of exposure and make every effort to maintain exposures as low as is technically feasible. The criteria and recommended standard will be reviewed and revised as new studies and data become available.

Other terms used for radiation (energy) in the frequency range of 300 kHz - 300 GHz (0.3-300,000 MHz) include RF, nonionizing electromagnetic radiation or energy, radiowaves, shortwaves, high frequency (HF), very high frequency (VHF), ultrahigh frequency (UHF), super high frequency (SHF), centimeter waves, and millimeter waves. Applications of radiofrequency and microwave radiation include television (TV) and radio broadcasting, communications, food processing and cooking, sealing and laminating operations, drying operations, medical diathermy, therapeutic hyperthermia, and radar.

Radiofrequency and microwave radiation may cause heating of the body at power densities in excess of 10 milliwatts per square centimeter (mW/cm^2). At certain frequencies, burns may result, and a heating sensation may be experienced at high RF and microwave exposure levels; at levels below about 10 mW/cm^2, incident RF/microwave radiation may not be perceived and adequate warning of exposure may not be given. The recommended standard is designed to protect workers from potential hazards resulting from RF- and microwave-induced heating and from other possible bioeffects that have been described in the literature. The reported effects include ocular changes, alterations in neuroendocrine function, alterations in the central nervous system (CNS), behavioral changes, changes in cardiac rate and hemodynamics, alterations in blood composition, changes in the immunologic system, embryotoxic effects, and reproductive effects. Further research is needed to more clearly determine the risks attributable to the effects of exposure to RF and microwave energy.

"Occupational exposure" to RF and microwave radiation is defined as exposure in any workplace where RF and microwave energy in the frequency range of 300 kHz - 300 GHz (0.3-300,000 MHz) is used or emitted above 0.1 of the occupational exposure limit (OEL) as defined in this document. Compliance with all sections of the recommended standard is required whenever and wherever there is occupational exposure to RF and microwave radiation. If exposure to other physical or chemical agents occurs, provisions of any applicable standards for such other agents shall also apply.

Section 1 - Workplace

(a) Recommended Occupational Exposure Limits

The values recommended apply to both continuous wave (CW) and pulsed wave (PW) radiation. For repetitively pulsed radiation sources with "short" pulse durations (ie, 0.5 second or less), the recommended limits apply to average values. For such repetitively pulsed radiation sources of RF/microwave energy, the average mean squared electric (E) or magnetic (H) field strength is calculated by multiplying the peak-pulse mean squared field strength value by the duty cycle. The duty cycle equals the pulse duration in seconds times the pulse repetition rate in cycles per second. The average plane-wave equivalent power density (see Chapters II and XII for definitions) is calculated by multiplying the peak-pulse power density by the duty cycle.

For frequencies of electromagnetic energy of 300 kHz (0.3 MHz) - 2 MHz, inclusive, the following values, as averaged over any 6-minute (0.1-hour) period, shall not be exceeded during a workshift of up to 10 hours: a mean squared E-field strength of 94,250 volts squared per meter squared (V^2/m^2) and a mean squared H-field strength of 0.663 amperes squared per meter squared (A^2/m^2). These values correspond to an equivalent plane-wave power density of 25 mW/cm^2. Measurement of power density alone is not sufficient for compliance with the recommendation in this frequency range; measurement of mean squared E-field strength and mean squared H-field strength is required.

For frequencies of electromagnetic energy between 2 and 10 MHz, the following values, as averaged over any 6-minute (0.1-hour) period, shall not be exceeded during a workshift of up to 10 hours: a mean squared E-field strength (in V^2/m^2) equal to $\frac{3,770\ (100)}{f^2}$, where f=frequency in MHz, and a mean squared H-field strength (in A^2/m^2) equal to $\frac{100}{(37.7)\ f^2}$. The equivalent plane-wave power density (in mW/cm^2) for these values can be calculated from the expression $\frac{100}{f^2}$. Measurement of power density alone is not sufficient for compliance with the recommendation in this frequency range; measurement of mean squared E-field strength and mean squared H-field strength is required.

For frequencies of electromagnetic energy of 10-400 MHz, inclusive, the following values, as averaged over any 6-minute (0.1-hour) period, shall not be exceeded during a workshift of up to 10 hours: a mean squared E-field strength (in V^2/m^2) of 3,770 and a mean squared H-field strength (in A^2/m^2) of 0.027.

These values correspond to an equivalent plane-wave power density of 1 mW/cm^2. Measurement of power density alone is not sufficient for compliance with the recommendation in this frequency range; measurement of mean squared E-field strength and mean squared H-field strength is required.

For frequencies of electromagnetic energy between 400 MHz and 2 GHz (2,000 MHz), the following values, as averaged over any 6-minute (0.1-hour) period, shall not be exceeded during a workshift of up to 10 hours: a mean squared E-field strength (in V^2/m^2) equal to $\frac{(3,770)\ f}{400}$, where f=frequency in MHz, and a mean squared H-field strength (in A^2/m^2) equal to $\frac{f}{(37.7)400}$. The equivalent plane-wave power density (in mW/cm^2) for these values can be calculated from the expression $\frac{f}{400}$. Measurement of either mean squared E-field strength or equivalent plane-wave power density is sufficient for compliance at frequencies of 400 MHz - 2 GHz. Measurement of mean squared H-field strength (H^2) is not required for compliance at frequencies between 400 MHz and 2 GHz until such time as equipment becomes commercially available for measuring H^2 in this frequency range.

For frequencies of electromagnetic energy of 2-300 GHz (2,000-300,000 MHz), inclusive, the following values, as averaged over any 6-minute (0.1-hour) period, shall not be exceeded during a workshift of up to 10 hours: a mean squared E-field strength (in V^2/m^2) of 18,850 and a mean squared H-field strength (in A^2/m^2) of 0.133. These values correspond to an equivalent plane-wave power density of 5 mW/cm^2. Measurement of either mean squared E-field strength or equivalent plane-wave power density is sufficient for compliance at frequencies of 2-300 GHz. Measurement of mean squared H-field strength (H^2) is not required for compliance at frequencies between 2 and 300 GHz.

The recommended OEL's are summarized in Table I-1 and illustrated in Figure I-1.

(b) Multiple Frequencies

For mixed (multiple) or broadband fields consisting of a number of frequencies for which there are different values of the OEL, the fraction of the OEL incurred within each frequency interval listed in Table I-1 shall be determined, and the sum of all such fractions shall not exceed unity. This provision requires that the fundamental frequencies of each source be determined.

(c) Partial-Body Exposure

In cases in which RF/microwave energy is incident to, and absorbed primarily in, localized portions of the body (partial-body exposure), sufficient information does not exist to identify the extent of any potential

TABLE I-1

RECOMMENDED OCCUPATIONAL EXPOSURE LIMITS

(As averaged over any 6-minute period)

Frequency (MHz)	Mean Squared Electric (E) Field Strength (V^2/m^2)*	Mean Squared Magnetic (H) Field Strength (A^2/m^2)**	Equivalent Plane-Wave Power Density (mW/cm^2)
0.3-2***	94,250	0.663	25
2-10***	$\frac{(3,770)\ 100}{f^2}$****	$\frac{100}{(37.7)\ f^2}$	$\frac{100}{f^2}$
10-400***	3,770	0.027	1.0
400-2,000*****	$\frac{(3,770)\ f}{400}$	$\frac{f}{(37.7)\ 400}$	$\frac{f}{400}$
2,000-300,000*****	18,850	0.133	5.0

*V^2/m^2 = volts squared per meter squared (field strengths are root mean square values)

**A^2/m^2 = amperes squared per meter squared (field strengths are root mean square values)

***Measurement of power density alone not sufficient for compliance at frequencies below 400 MHz

****f = frequency in MHz

*****Measurement of either mean squared E-field strength or equivalent plane-wave power density is sufficient for compliance at frequencies above 400 MHz. Measurement of mean squared H-field strength is not required for compliance at frequencies above 400 MHz.

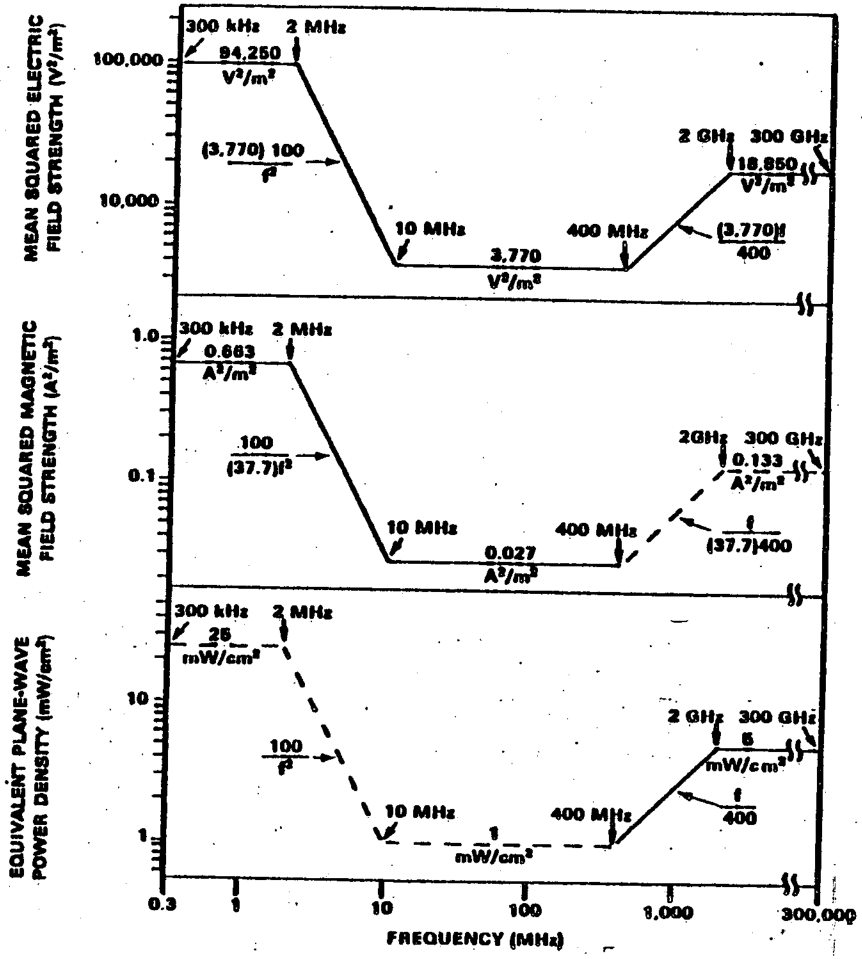

FIGURE I-1. RECOMMENDED EXPOSURE LIMITS, f = FREQUENCY IN MHz. Broken lines indicate limits for which measurements are either not required or not sufficient for compliance (see text).

hazards. Therefore, until further data become available on this subject, NIOSH does not recommend that separate standards be established for partial-body exposure.

(d) Action Level

Concern for the health and safety of employees requires that protective measures be instituted so as to ensure that the exposure in the workplace remains at or below the enforceable limit. As the result of a study of the probability that at least 5% of actual workday exposures of employees to toxic substances would exceed the standard when various fractions of the OEL were assumed to have been measured on a single day, a concentration one-half that of the recommended OEL appeared to be satisfactory to indicate, on the basis of occasional samples, when the concentration of a hazardous chemical to which employees are exposed approaches the OEL (*@MR3133*). For exposure of workers to RF/microwave energy, this same fraction is applied as an action level that is used to trigger monitoring activities that are not required for employees exposed to RF energy at or below the action level. Areas in which E- and H-fields have mean squared field strengths (or power densities where applicable) greater than the action level are required to be identified by warning signs and to be subject to industrial hygiene surveys every 6 months.

(e) Monitoring

The instrumentation and measurement techniques described in Chapter XI, or techniques of at least equal sensitivity, shall be used to determine OEL's of RF and microwave radiation. After promulgation of a standard based on these recommendations, the employer shall be required to list each operation in which RF or microwave energy is used and all employees who may be at risk of exposure to such energy. Measurements of RF and microwave energy shall be made in all locations listed. All areas in which exposures exceed the action level and all employees who have access to these areas shall then be subject to the remaining provisions of this standard.

Section 2 - Medical

Medical surveillance shall be made available to personnel at risk of exposure to RF and microwave energy. Thorough medical and work histories and physical examinations are suggested despite the lack of well-defined health effects correlated with exposure of humans to RF and microwave radiation. Inclusion or exclusion of any or all of the tests recommended as part of the examination shall be at the discretion of the responsible physician.

(a) Procedures suggested for the medical examination include the following:

(1) Laboratory examinations, including urinalysis, hematocrit, white blood cell (WBC) count, differential blood cell count, and analysis of serum for total protein, blood urea nitrogen (BUN), glucose, albumin, globulin, tetraiodothyronine (T_4), electrolytes, triglycerides, cholesterol, and free fatty acids.

(2) Evaluation of cardiovascular function, including an electrocardiogram (ECG).

(3) Evaluation of neurologic function, including an electroencephalogram (EEG). An emotional and behavioral profile shall be compiled with attention to such factors as weakness, headache, memory impairment, inattention, insomnia, and irritability.

(4) Examination of the skin and eyes for evidence of significant exposure to RF and microwave energy, ie, erythema or burns of the skin, corneal and lenticular opacities, and conjunctival and corneal injections.

(b) Preplacement examinations shall be made available to all new employees. The examination shall consist of the medical evaluation detailed in (a) and shall include also comprehensive medical and work histories, with particular attention given to previous exposures to ionizing and nonionizing radiation.

(c) Annual medical examinations consisting of the procedures described in (a) shall be made available to all workers exposed to RF and microwave radiation at mean squared field strengths above the action level. Work histories shall be updated at this time. Medical examination of employees who are exposed at mean squared field strengths at or below the action level is suggested.

(d) Exposure above the permissible limits shall be followed within 3-7 days by an examination consisting of the evaluation suggested in (a). A followup examination is suggested within 1-2 months postexposure but shall be performed at the discretion of the responsible physician. Determination that exposure above the limits has occurred shall be performed according to the protocol of Section 1(f). Additional diagnostic procedures that may be useful in assessing the severity of the effects from such exposures include estimation of the concentrations of protein-bound iodine (PBI), of triiodothyronine (T_3) or T_4 in serum, or of vanillylmandelic acid (VMA) in urine.

(e) Medical records including health and work histories shall be maintained for at least 30 years after employment ends for all persons occupationally exposed to RF and microwave radiation. The records shall be made available, on request, to the designated medical representatives of the

Secretary of Health, Education, and Welfare, of the Secretary of Labor, of the employer, and of the employee or former employee.

Section 3 - <u>Labeling and Posting</u>

(a) All warning signs shall be printed in both English and the predominant language of non-English-reading workers. The design recommended by OSHA (29 CFR 1910.97) shall be adopted for all warning purposes, with the exception that the words "RADIOFREQUENCY RADIATION" replace "RADIOFREQUENCY RADIATION HAZARD."

(b) Areas in which exposures have been determined to be above the action level shall be posted. Labels on devices emitting RF or microwave radiation are not considered necessary. The sign described in (a) shall be of such size as to be recognizable and readable from a distance of 3 m (10 feet).

(c) Areas in which RF or microwave energy exists at levels above the recommended limits also shall be posted. In this case, the warning sign shall contain the following additional instruction: HAZARD--UNAUTHORIZED PERSONNEL FORBIDDEN TO ENTER. The sign must be readable from a distance of 3 m (10 feet). The perimeter of the restricted area shall be clearly demarcated with signs visible to all personnel approaching the area.

Section 4 - Informing Employees of Hazards

(a) The employer shall be responsible for informing all new and present employees of the techniques of monitoring for and the potential biologic hazards of exposure to RF and microwave radiation. Oral instruction by knowledgeable individuals qualified by training or experience is required for all personnel potentially occupationally exposed to RF and microwave energy and may be supplemented with written information.

(b) Methods for avoiding exposure, such as those dictated by the recommended work practices (see Section 5) and by the restrictions or prohibitions placed on activity in properly posted areas (see Section 3), shall be emphasized. The utility of various engineering controls (see Section 6) shall be discussed also. Results of health examinations and radiation monitoring shall be made available to each occupationally exposed employee.

Section 5 - Work Practices

Appropriate work practices shall be prescribed to limit unnecessary exposure to RF and microwave energy. Their scopes should depend on the engineering controls available. A proper and effective combination of safe practices and efficient controls, which may differ for each exposure situation, is desirable.

(a) Where possible, sources of RF and microwave energy shall be switched "off" when not being used. Maintenance of generating, transmitting, and radiating equipment shall be performed, whenever possible, while such equipment is not in operation. Since electronic adjustment or tuning is not always possible in an unpowered mode, dummy loads or other engineering controls shall be added where necessary.

(b) When possible, access to the vicinity of equipment producing RF and microwave radiation above the action level shall be limited to operators and maintenance, industrial hygiene, or safety personnel. Equipment shall not be operated until such time as those employees leave any area to which access is prohibited under normal use conditions. Use of the equipment shall be restricted to properly trained and qualified personnel.

Section 6 - <u>Engineering Controls</u>

Control of the emission of RF or microwave radiation from generating, transmitting, and radiating equipment should rely on the proper application of engineering principles. Controls such as those described below are considered to be the most effective way of limiting exposure.

(a) Shielding may consist of metal sheets, wire mesh, metallized fabrics, or metal-coated glass, plastic, or other materials. Where possible, shields shall be placed around all equipment surfaces to minimize occupational exposure due to RF and microwave radiation emitted from reflecting and scattering surfaces and secondary sources as well as from the equipment. All shielding material shall be properly installed and grounded. Absorptive paints or other coatings may be applied to potential scattering or reflecting surfaces near microwave radiation-emitting equipment.

(b) If not provided by the equipment manufacturer, additions including wavetraps, dummy loads, grounded curtains, choke seals, and deflecting elements shall be made, where necessary, to redirect radiation emitted from doors, ports, or other openings away from potentially occupationally exposed employees.

(c) Interlocks shall be provided on all chamber- or oven-type equipment to stop generation of RF or microwave fields by the source unless the chamber is closed, and to shut off such equipment if the door is opened.

(d) Use of shielding, equipment modifications, or interlocks is required in situations in which occupational exposures to RF and microwave energy may exceed the recommended limit and where safe work practices are not feasible.

Section 7 - Monitoring and Recordkeeping

The monitoring methods described in Chapter XI shall be followed in performing surveys of RF and microwave fields.

(a) Areas in the occupational environment in which the levels of RF and microwave energy have been determined to be above the action level and at or below the OEL shall be surveyed every 3 months. Within 1 week following a physical or electronic alteration of the equipment or an alteration in the process, a complete survey must also be performed. Records of the measurements shall be made as described in Chapter XI.

(b) If measurements taken during a survey indicate that occupational exposures exceed the recommended limit, use of all equipment producing excessive fields shall be prohibited until appropriate controls, such as described in Section 6, have been instituted.

(c) Records shall contain all information described in Chapter XI, plus the date and time of measurement, the monitoring equipment used, the employees' names, and the actions taken, if any. These records shall be made available, on request, to designated representatives of the Secretary of Health, Education, and Welfare, the Secretary of Labor, the employer, and the employee or former employee.

II. PHYSICAL PRINCIPLES AND EXTENT OF EXPOSURE

Definition, Propagation, and Transmission of Electromagnetic Waves

Energy can be propagated through space by means of electric (E) and magnetic (H) fields that vary with time. The fields are interrelated, since a changing E-field induces a change in the H-field and vice versa. A disturbance in either an E- or an H-field will result in the propagation of energy in a wavelike manner. Such waves are known as electromagnetic waves. Electromagnetic waves are classified further by their frequency and wavelength. Frequency is defined as the number of complete cycles of the E- or H-field per second (measured in hertz, Hz; 1 Hz = 1 cycle/s). Wavelength is the distance in a single propagating wave between two consecutive maxima or minima of the E-field or H-field. Frequency is related to wavelength by the formula f=c/wavelength, where c is the speed of propagation of light (practically considered to be a constant). Units of frequency commonly used for RF and microwave radiation are kHz (10^3 Hz), MHz (10^6 Hz), and GHz (10^9 Hz).

Since the magnitude and direction of the E- and H-fields are continuous functions defined at each point of the wave, they are vector quantities. A typical plane electromagnetic wave is characterized by the following properties: (1) the E-field is perpendicular to the H-field; (2) the direction of propagation is perpendicular to both the E- and H-fields, and no E- or H-field exists in the direction of propagation; (3) the velocity of propagation in free space is about $3x10^8$ m/s--in other media, the velocity of propagation depends on the properties of the medium; (4) the ratio of the E-field strength to the H-field strength is constant, and (5) the maximum energy stored in the E-field per unit volume is equal to the maximum energy stored in the H-field per unit volume.

For the purpose of this document, RF and microwave radiation will be defined as electromagnetic radiation in the frequency range of 300 kHz -300 GHz (0.3-300,000 MHz). The wavelengths corresponding to these frequencies range from 1 km to 1 mm, and the quantum energy content of these waves varies from about 10^{-9} electron volts (eV's) at the lower frequency to about 10^{-3} eV at the high frequency end of the range of frequencies considered in this document. Since the energy required for the ionization of an atom is 1 eV or more, microwave radiation is not capable of producing ionization in biologic tissue. For this reason, this type of electromagnetic radiation is often referred to as "nonionizing" radiation.

Radiation in the microwave region has been associated with various frequency bands that have been given in the past the alphabetic notations shown in Table II-1. In addition, terms sometimes used in the United States to designate frequencies within the range of this document, together with typical uses of these frequencies, are presented in Table II-2.

TABLE II-1

ALPHABETIC DESIGNATIONS FOR VARIOUS FREQUENCIES

Early Band Designations	Approximate Frequency Range (GHz)
L	1.0-2.0
S	2.0-4.0
C	4.0-8.0
X	8.0-12.0
K_u	12.0-18.0
K	18.0-27.0
K_a	27.0-40.0
millimeter	40.0-300.0

Adapted from reference @MR1611

The classification scheme used in literature published in the Soviet Union for frequencies in the microwave region is shown in Table II-3 (*@MR1984*).

Frequency of RF/microwave radiation is an important factor in determining the extent of the "near field" (see Chapter XI) of a radiating source. Transmitting antenna size is also important, and its influence may be detected at

TABLE II-2

US DESIGNATIONS AND USES OF FREQUENCIES

Designation	Frequency Range (MHz)	Typical Uses
Low to medium frequency	0.1-3	Amplitude-modulated (AM) radio, radio-navigation, radio communications
HF ("shortwaves")	3-30	Industrial heating, welding, and gluing; broadcasting, medical diathermy
VHF	30-300	Many of above uses, frequency-modulated (FM) radio and TV, air traffic control, radar
UHF	300-3,000	Microwave ovens, radar, TV, telecommunication
SHF	3,000-30,000	Radar, satellite-earth communication, point-to-point telecommunication
Extremely high frequency (EHF)	30,000-300,000	Radioastronomy, radio-meteorology, radio-spectroscopy

Adapted from reference @MR1984

distances of several wavelengths or more from the source. In the "far field" (see Chapter XII) of a transmitting antenna, ie, several wavelengths' distance or more from the antenna, the power density is often used to measure energy

TABLE II-3

USSR DESIGNATION OF FREQUENCIES

Designation	Approximate Frequency Range (MHz)
Low frequency	0.02 (and below) - 0.05
HF	0.05-20
UHF	20-300
SHF	300-390,000

Adapted from reference @MR1984

flux density. Power density is expressed as power per unit area, eg, milliwatts per square centimeter, and, in the far field, E-field and H-field intensities are related to power density by the following formula:

$$P_r = \frac{E^2}{Z_o} = H^2 Z_o$$

where:

P_r = average power density in the far field at a distance r from the radiating source

E = rms (root mean square; see Chapter XII for definition) value of the E-field at distance r

H = rms value of the H-field at distance r

Z_o = the impedance of free space, 377 ohms

However, in the near field of an RF/microwave source, ie, within several wavelengths, the relationship between power density and field strength is more complex, and measurements of the E-field strength and H-field strength are necessary to characterize exposure conditions properly. The commonly used unit of measurement for E-field strength is volts per meter (V/m) and that for H-field strength is amperes per meter (A/m).

Several devices exist for producing RF and microwave energy. The four basic types are power-grid tubes, linear-beam tubes such as klystrons, crossed-field devices such as magnetrons and amplitrons, and solid-state devices. Most industrial microwave applications involve the use of linear-beam tubes and crossed-field devices. Microwave power tubes generally operate at voltages greater than 1 kV, and some industrial and consumer applications of microwaves use tubes with power outputs of up to 50 kW.

Microwave tube technology is fairly well advanced. However, solid-state microwave devices have been widely developed only in the past 15-20 years. Common industrial solid-state devices include transistors for applications below 1 GHz and avalanche diodes (IMPATT and TRAPATT) for applications above 1 GHz. These devices are relatively expensive for operations requiring high power outputs and therefore are generally used in applications involving only a few watts of output power.

After generation, microwaves are usually transmitted to an applicator or antenna through a waveguide or coaxial transmission line. Waveguides are rectangular, elliptical, or circular and are made from a conducting metal, such as aluminum, brass, or copper, or from a nonconducting substance with a thin conducting coat on its inner surface. The waveguide is at ground potential, and it allows the transmission of high power over distances on the order of 3 to about 100 m. For example, a 4.3- x 8.6-cm rectangular waveguide operating at 2.45 GHz can efficiently transmit several megawatts of power. Coaxial cables contain both inner and outer conductors. They can carry over 1 kW of power at 915 MHz but are not efficient transmitters at higher frequencies. They are generally used for longer distance energy transmission at lower frequencies or for transmission of energy over short distances at higher frequencies.

Radiating antennas are used to transmit microwave energy through free space or through a dielectric material. An example of such an antenna is a parabolic reflector. Energy transmitted in this way can be modulated appropriately for use in communications, radar, navigation, etc, or it can be applied to dissipative materials for purposes of conversion to another form of energy such as heat.

Several devices have been designed for the commercial application of microwave energy to materials that require heating or cooking (*@MR0348*). The specific type of applicator used depends on the properties of the product being irradiated and the desired result. For example, microwave ovens illustrate a specialized use of the multimode cavity to deliver microwave energy to food.

Extent of Exposure and Uses of Radiofrequency and Microwave Radiation

One of the largest uses of RF and microwave radiation has been in the area of communications and broadcasting. Table II-4 presents frequencies assigned for commercial radio and TV transmission in the United States (47 CFR 2.106).

TABLE II-4

FREQUENCIES ASSIGNED FOR COMMERCIAL RADIO AND TELEVISION TRANSMISSION IN THE UNITED STATES

(Standard Broadcast Band)

Frequency	Band
535 kHz - 1.605 MHz	Radio-AM
88-108 MHz	Radio-FM
54-72 MHz	TV-VHF
76 MHz	"
174-216 MHz	"
470-890 MHz	TV-UHF

In 1969, the Bureau of Radiological Health (BRH) of the US Food and Drug Administration (FDA) determined that there were 71,524 microwave towers in the United States using 191,517 separate frequencies (*@MR1453*). This report also noted that there were 16,272 broadcasting stations in the country at that time, including AM and FM radio stations and commercial and educational TV stations. However, this figure is apparently exaggerated, and the correct number is close to 9,700 (J Cohen, written communication, December 1979). BRH also reported that in 1969 there were 2,897 fixed radar installations in the United States. The latter figure did not include mobile, vehicular, and waterborne radar operations or classified military communications facilities. Since the time of the BRH report, the demand for microwave use in communications has increased tremendously. A recent report listed 9 million transmitters, hundreds of thousands of microwave communications towers, tens of thousands of radar antennas, and almost 30 million citizens band (CB) radios in the United States (*@MR3006*).

The Federal Communications Commission (FCC) has designated certain frequencies for unlicensed use in industrial, scientific, and medical applications. These are sometimes referred to as the "ISM" bands. The ISM frequencies are as follows (47 CFR 18.13): 13.56 MHz ± 6.78 kHz, 27.12 MHz ± 160 kHz, 40.68 MHz ± 20 kHz, 915 MHz ± 13 MHz, 2.45 GHz ± 50 MHz, 5.80 GHz ± 75 MHz, and 24.125 GHz ± 125 MHz.

A major use of microwave energy is in the processing and cooking of food (*@MR0300*). In addition to home and industrial cooking, microwaves are used in many phases of the food-processing industry, such as the finish baking of crackers and biscuits, "proofing" yeast-raised doughnuts, baking and proofing bread, sterilizing food, blanching vegetables, defrosting frozen foods and meats, dehydrating such foods as fruits and potatoes, freeze-drying foods, finish drying potato chips, precooking poultry, precooking bacon, determining fat content in meat, and cooking sausage.

Microwaves are used to dry numerous other materials. In the forest products industry, microwave energy is used for hardwood and veneer drying, as well as for glue setting. Microwaves also provide heat for the drying of paper, moisture leveling in paper, and ink drying in the newspaper industry. Other applications include the drying of leather, textiles, plastic resins, and ceramic tape.

In the plastics and rubber-products industries, RF and microwave energy is widely used in sealing and fusing applications. Radiofrequency and microwave energy is especially well suited for this purpose due to its production of rapid and concentrated internal heating; it is also used in the curing or postpolymerization of various materials, such as plasticized polyvinyl chloride, wood resins, polyurethane foam, concrete binder materials, rubber tires, and epoxy resins.

Many industrial microwave heating systems operate at frequencies of 915 MHz or 2.45 GHz. Other systems, particularly those involving such jobs as sealing plastics and gluing, operate in the range of 13-100 MHz.

Radiofrequency and microwave radiation has been used for many years in medical diathermy. Diathermy devices are primarily used for physical therapy and in the treatment of such diseases as arthritis. More recently, diathermy-type devices have been used experimentally in the treatment of certain tumors.

There are numerous situations in which workers are exposed to RF and microwave radiation. Table II-5 provides a list of occupations involving specific activities or products in which RF and microwave radiation may be present.

The exact number of workers exposed to RF and microwave radiation is not known. An estimate of 21 million potentially exposed workers was made in 1977 (*@MR0353*). This figure included all major occupational categories and should probably be regarded as an upper limit.

TABLE II-5

POTENTIAL OCCUPATIONAL EXPOSURES TO

RADIOFREQUENCY AND MICROWAVE RADIATION

Automotive workers
- Drying of trim base panels
- Embossing of heel pads to carpets
- Heat sealing body interior trim panels
- Heat sealing convertible tops and vinyl roofs
- Heat sealing upholstery covers for seats and backs

Communications workers involved in operation/maintenance of:
- Commercial radio and TV broadcasting transmitters
- Earth-satellite ground stations
- Microwave relay towers
- Mobile transmitters (including hand-held models)
- Point-to-point transmitters
- Radar systems

Food products workers
- Finish drying of "polished" baked goods
- Inhibiting enzyme action
- Melting chocolate prior to tempering
- Thawing frozen baked goods

Furniture and wood workers
- Decking assembly
- Door lamination
- Fabrication of posts and rafters
- Fiberboard fabrication
- Laminated beams
- Lumber edge gluing
- Plywood panel patching
- Plywood or particle-board scarf gluing
- Ski lamination
- Veneer panel gluing

Glass fiber workers
- Drying and curing sizing on machine packages
- Drying coatings on continuous moving strands
- Drying glass fibers on forming tubes
- Drying roving packages

Paper products workers
- Correcting moisture profile on continuously moving webs
- Drying resin coatings
- Drying twisted twine packages
- Gluing paper
- Heating coating on continuous webs

RF/microwave application workers
- RF-excited gas display signs used in advertising
- Drying of ceramic objects
- Activation of chemical reactions
- Electronic tube aging and testing
- RF-excited gas lasers
- Diathermy and (experimental) cancer therapy
- Low-temperature ashing of scientific samples
- RF-stabilized welding

Rubber products workers
- Drying latex foams
- Gelling latex foams
- Preheating prior to curing latex foams
- Preheating prior to molding

Textile workers
- Drying continuous webs
- Drying impregnated or coated yarns
- Drying rayon cake packages
- Drying slasher coatings
- Drying wound packages

TABLE II-5 (CONTINUED)

POTENTIAL OCCUPATIONAL EXPOSURES TO

RADIOFREQUENCY AND MICROWAVE RADIATION

Workers involved in heat sealing and dielectric heating of plastic in the manufacture/fabrication of:

- Acetate box covers
- Advertising novelties
- Appliance covers
- Appliance handles
- Aprons
- Baby pants
- Beach balls
- Belts and suspenders
- Blister packages
- Book covers
- Capes
- Charge cards
- Checkbook covers
- Convertible tops
- Cushions
- Diaper bags
- Display boxes
- Electric blankets
- Food packages
- Fountain pens
- Garment bags
- Gas masks
- Goggles (industrial)
- Handbags
- Hat covers
- Index cards
- Lampshades
- Liquid containers
- Luggage
- Machine covers
- Mattress covers
- Milk cartons
- Oxygen tents
- Packages
- Pharmaceuticals
- Pillowcases
- Pillow packages
- Plastic gloves
- Pool liners
- Protective clothing
- Racket bags
- Rain apparel
- Refrigerator bags
- Shoe bags
- Shoes
- Shower curtains
- Slipcovers
- Splatter mats
- Sponge backings
- Sports equipment
- Telephone equipment
- Tobacco pouches
- Toys
- Travel cases
- Umbrellas
- Wallets
- Waterproof containers
- Wire terminal covers

Adapted from reference @MR0946

III. BIOLOGIC EFFECTS OF EXPOSURE

Biophysical Principles

Existing data suggest that death of biologic tissue resulting from exposure to RF/microwave energy involves the irreversible thermal denaturation of biologic macromolecules such as proteins (*@MR3129*). Thermally induced alterations in biologic materials are also important at sublethal levels of exposure. In addition, the internal distribution of absorbed energy may result in increased energy deposition in individual cells (or groups of cells), in sensitive organs, or in certain areas of the body. Such differential distribution of energy could lead to the production of specific biologic effects, eg, those reported to occur in the CNS, after exposure to RF/microwave energy.

In general, mechanisms of interaction of RF/microwave energy with biologic matter are not well understood (*@MR3129*). Proposed mechanisms include field-induced disruption of noncovalent macromolecular bonds such as hydrogen bonds and hydrophobic interactions, disruptions of bound water, quantum effects such as proton "tunneling," membrane depolarization of nerve cells resulting from the direct interaction of E- or H-field components with neuronal elements, and alterations in other biologic membranes. A well-characterized interaction mechanism is that of field-induced rotation and dielectric relaxation of polar molecules. The extent to which this phenomenon can result in disturbance of biologic function is not clear, however. Further discussion of these and other possible biophysical mechanisms can be found in the proceedings of a 1978 workshop sponsored by the FDA's Bureau of Radiological Health and the Department of the Navy (*@MR3128*). Future research needs in the study of interaction mechanisms of RF/microwave energy are discussed in Chapter IX of this document.

The extent of a biologic effect due to electromagnetic radiation is often assumed to depend, at least in part, on the extent to which the incident electromagnetic energy is absorbed. However, the absorption of energy does not necessarily result in the production of an observable biologic effect. Absorption of electromagnetic energy has been shown to depend on the frequency of the radiation and on the size, shape, orientation, and dielectric properties of the object(s) being irradiated (*@MR0423,@MR0604,@MR0731,@MR0732,@MR2925*). In humans, data derived from the use of models have indicated that the maximum specific absorption rate (SAR) for whole-body irradiation occurs between 60 and 100 MHz with a peak at about 70 MHz (*@MR2089,@MR2925,@MR3086*). The SAR (commonly expressed as watts per kilogram) is that quantity of electromagnetic energy absorbed by a body per unit of mass during each second of time. The exact shape of the absorption curve depends on the size and shape of the individual being irradiated (*@MR2925*). Local absorption in the legs and neck of humans reportedly is higher than whole-body average absorption at frequencies near 70 MHz (*@MR1896,@MR3090*). Modeling data, described in 1977 and 1978, identified a resonant frequency for the intact human arm at about 150 MHz (*@MR1896*) and for the intact adult human head at about 350 MHz (*@MR3027*). At frequencies below about 30 MHz and above about 500 MHz, much less incident radiation appears to be absorbed than at the resonant frequencies (*@MR2768,@MR2925,@MR2089*).

Maximum absorption of electromagnetic energy in small animals reportedly occurs in the frequency range of about 0.5-3 GHz (*@MR0473,@MR2925*). As with humans, whole-body absorption by animals depends on several factors, including frequency, size, shape, and orientation. Approximate frequency ranges of maximum absorption have been determined, based largely on modeling data, for dogs (100-300 MHz), monkeys (100-400 MHz), rabbits (300-700 MHz), guinea pigs (500-800 MHz), rats (0.5-1 GHz), and mice (1-3 GHz).

Energy deposition from portable radio transmitters has been studied by using phantom models of the human head (*@MR3036,@MR3037*). Such an RF transmitter, operating at 840 MHz and 6 W (radiated power) and held 0.5 cm from the mouth of a phantom, resulted in a temperature maximum (increase of 0.03-0.04 C) 2-3 cm beneath the surface of the frontal bone. When held properly (about 5 cm from the mouth), thermal deposition of energy was nearly unmeasurable.

A 6-W portable radio with a VHF helical antenna (frequency about 150 MHz) resulted in a temperature increase in simulated biologic tissue of less than 0.1 C when held about 0.5 cm from the mouth of a head phantom for 1 minute

(*@MR3036*). No detectable increase was noted in the immediate vicinity of the eye. Balzano et al concluded that a health hazard would be present only if the user placed the tip of the antenna near the eye (a distance of about 0.5 cm or less) while operating the transmitter.

Modeling data based on the use of prolate spheroids have shown that absorption varies according to the polarization of the incident wave, with maximum absorption occurring when the E-vector is coplanar with the long axis of the spheroid (*@MR2089,@MR2925*). Ground resistance can alter resonant frequencies (*@MR2925*). Maximum absorption in the presence of ground effects occurs at frequencies approximately one-half those for bodies isolated in free space (*@MR2089*).

Certain early papers are somewhat at variance with the more recent information on absorption of RF energy. For example, Schwan and Li (*@MR1337, @MR1338*), in 1956, reported that radiation at frequencies from 1 to 3 GHz may be absorbed completely, depending on the specific frequency, skin thickness, and thickness of subcutaneous fat. At frequencies below 500 MHz, absorption was estimated to be 30-50% of incident radiation. In general, according to the authors, absorbed radiant energy at frequencies below about 1 GHz is transformed into heat primarily in the deeper body tissues, and microwave energy at frequencies above 3 GHz is absorbed primarily on the surface of the skin where the dissipation of heat is relatively efficient.

At frequencies below 1 GHz, Schwan and Li (*@MR1338*) estimated that an incident power density of 30 mW/cm^2 could be tolerated. For frequencies of 1-3 GHz, this estimate was lowered to 10 mW/cm^2; for frequencies above 3 GHz, the estimated tolerable level was 20 mW/cm^2 or more. Based on these estimates, Schwan and Li suggested that a tolerable human dosage for the frequency range of 400 MHz (or lower) - 3 GHz (and above) should be 10 mW/cm^2.

According to a 1969 paper by Schwan (*@MR1326*), the depth of penetration of microwave radiation in fatty tissue and tissue with a high water content is sharply diminished at frequencies above about 0.5-1 GHz. Radiation at frequencies above 10 GHz was found to be absorbed completely by the skin and to cause only surface heating.

A similar inverse relationship between penetration depth and frequency was shown by Guy et al (*@MR0937*), in 1974, for frequencies between 27 MHz and 2.45 GHz. The depth of penetration in muscle and fat was considerably diminished at the higher frequencies (about 0.4-3 GHz).

Historical Reports

Much of the early work with RF and microwave radiation concerned its use in the therapeutic heating of biologic tissues. Many of the qualitative observations made during such treatments have been subject to subsequent experimentation. In 1893, D'Arsonval (*@MR1805*) reported on a new method of electrotherapy using large solenoids that were not brought into contact with the body. The frequency-dependent nature of the absorption was recognized by 1936 (*@MR0556*) and discussed with regard to the relative effectiveness of this type of therapy. In addition, by the 1940's, some indication of the deleterious effects of RF and microwave radiation emerged (*@MR1068*).

In 1930, Carpenter and Page (*@MR0497*) described the results of initial attempts to induce fever in humans by RF radiation. At an E-field strength of 4 kV/m, a frequency of 10 MHz was found to be more effective than were higher frequencies. Following a report of certain subjective symptoms in personnel testing RF apparatus at the Naval Research Laboratory, Bell and Ferguson (*@MR0921*), in 1931, requested five volunteers to submit to as much VHF irradiation as could be tolerated. The men stood 1.3 m from an RF transmitter generating 55-MHz radiowaves at output power levels ranging from 10 to 18.5 kW. Each held a metal rod (to serve as an antenna) in one hand. The effects observed and the order in which they progressed during irradiation were (1) warmth and discomfort in the hand holding the rod, followed by a sensation of warmth in other parts of the body, (2) cramps in that hand, (3) sweating, and (4) fatigue, drowsiness, and headache. Bell and Ferguson stated that their observations and tests were the first to be published concerning possible health hazards of workplace exposure to radiation from RF transmitters. They pointed out the similarity of the symptoms to those of heatstroke and suggested a psychogenic origin for the responses.

Fever therapy was used to treat a variety of conditions in the early part of this century (*@MR0446*). In 1934, Bierman (*@MR0441*) reported on several consequences of irradiation of 24 patients suffering from a variety of diseases. A temperature increase of approximately 3.6 C was produced by 10-MHz irradiation. The general response consisted of an initial decrease in leukocyte count followed by an increase. This biphasic response was repeated in turn by neutrophils, then by monocytes, and finally by lymphocytes. Bierman interpreted the results as indicating that the bone marrow was the first immunogenic tissue to be affected by RF radiation. Repeated exposures diminished the stimulatory response. Changes in leukocyte count following hyperpyrexia induced by diathermic electric currents also were reported by Jung (*@MR1036*) in 1935.

Bierman et al (*@MR0440*), in a 1935 report, described an instrument called the "radiotherm" used to produce fever for the treatment of venereal infection. The apparatus consisted of a 1-kW oscillator operating at 10 MHz with various condenser plates, cuffs, and electrodes. Average increases of 3.5 C in the rectal temperatures and of 2 C in the oral temperatures of 50 female patients were recorded during an average exposure of 53 minutes. Shortwave radiation-induced fever had been observed to be beneficial in the treatment of allergic diseases such as asthma and hay fever. In 1935, Wilmer and Miller (*@MR1490*) suggested, however, that the nature of such mechanically (sic) produced fevers was different from that encountered in a physicochemical fever.

The wide applicability of shortwave (20-150 MHz) therapy was reviewed by Stiebock (*@MR1407*) in 1935. However, during a discussion in the same year of the efficacy of physical therapy for the treatment of chronic diseases, Leavy (*@MR1191*) mentioned some limitations on the use of shortwave diathermy. He emphasized that the excessive heat generated was not tolerated by patients with some cardiac disorders, pulmonary diseases, or functional neuroses or by those of advanced age, whereas it was beneficial to those with arthritis, articular diseases of the spinal cord, angina pectoris, synovitis, peripheral vascular diseases, and fractures.

Coulter and Carter (*@MR0556*), in a 1936 report, compared the relative effectiveness of 50-, 25-, 16.67-, and 12.5-MHz radiation for diathermic applications. The temperatures in the muscle, in the subcutaneous region, and on the surface of the skin of the thighs of six volunteers were measured. The elevation of temperature induced in the deep muscle increased with frequency, whereas that induced in the skin decreased. Reiter (*@MR1264*) in the same year described the use of shortwave diathermy for treatment of chronic brain diseases. The conditions of schizophrenics and patients suffering from parkinsonism, syphilis, paralysis, and optic atrophy reportedly were improved by repeated short irradiations with 20 and 75 MHz. No changes in rectal temperature, in the concentrations in the blood of a variety of constituents, or in the usual measures of cardiovascular dynamics were noted during or following treatment.

Hyperpyrexia induced by shortwave irradiation was assumed by MacLeod and Hotchkiss (*@MR1068*), in 1941, to inhibit spermatogenesis. Two volunteers were placed in a fever cabinet and exposed to RF radiation until their body core temperatures reached 40.5 and 41 C within about 45 minutes after the start of exposure. Their sperm counts remained normal for approximately 18 days but then dropped to a minimum between 44 and 50 days after exposure. The delay in the observed effect was due to the cyclic nature of spermatogenesis. The results suggested thermal effects on the germinal epithelium of the testes.

Daily (*@MR0569*), in 1943, presented the results of a clinical study of male naval personnel exposed to radar and HF radiation. The symptoms reported by the workers, who had been exposed for 1-8 h/d for 2-108 months, included headaches (22%), a flushed feeling (4%), and an increased sensation of heat about the face and extremities (7%). No evidence of hematologic, reproductive, or dermatologic abnormalities due to microwave exposure was found. A 1945 survey by Lidman and Cohn (*@MR2097*) of US naval personnel assigned for 2-36 months to various duties involving radar indicated no effects on erythropoiesis or leukopoiesis.

In a 1948 analysis of microwave heating of human tissues, Horvath et al (*@MR0833*) recommended the use of 2.45-GHz radiation for selective local heating. The largest temperature increases occurred in the subcutaneous tissue (up to 10.7 C) and muscle (up to 4.0 C) and were not accompanied by increased rectal temperature or vasodilation. Despite measurable temperature increases at depths up to 6 cm, the volunteers subjectively reported only a pleasant warmth in the skin. Similar findings were reported in 1948 by Osborne and Frederick (*@MR1171*), who measured temperatures of up to 40.1 C at a depth of 5.1 cm following microwave irradiation.

Wakim et al (*@MR1494*), in 1948, described large increases (average 81%) in peripheral blood flow during shortwave diathermy of human limbs. These were still evident 20-30 minutes after irradiation had been halted and were accompanied by increases in oral temperature of 0.5-1.2 C. Flax et al (*@MR0689*), in 1949, presented the results of diathermic treatment of 10 patients. No correlation was noted between the observed elevations in tissue temperature, which averaged 4 C at a depth of 2.5 cm following 20 minutes of treatment, and blood flow.

Human Case Reports

The possibility of microwave-induced internal heating was discussed in a 1957 report by McLaughlin (*@MR1155*) describing a fatality associated with a severe exposure to microwave radiation. A 42-year-old male worker inadvertently stood directly in the beam of a radar transmitter (frequency of the radiation not specified) within 3.1 m of the antenna. Within a few seconds, he experienced a sensation of abdominal heat, and shortly thereafter the heat became intolerable, forcing him to move away. Within 30 minutes, he developed acute abdominal pain and began vomiting. When examined an hour after exposure, the patient was in mild shock. His blood pressure was 90/30 mmHg, his radial pulse rate was 72, and he had atrial fibrillation. The patient was subsequently admitted to a hospital, at which time his abdomen was greatly distended and had the general appearance associated with acute peritonitis. His leukocyte count was 15,700/mm^3. The patient underwent an operation about 6 hours after the beginning of pain, and at this time, his appendix was removed. Several days later, evidence of bowel obstruction was found. Subsequent evisceration through the abdominal wound forced a second operation, at which time an oval perforation was found in the bowel. The patient went into shock and died within 24 hours. The author concluded that the cooked and hemorrhagic appearance of the bowel and the pathologic reports were consistent with a local absorption of heat due to whole-body irradiation. He also noted that hemorrhagic infarcts of the spleen observed in the patient were similar to those seen by him in two other patients exposed to microwave radiation. This report has been criticized by Ely for reaching conclusions that may be misleading (*@MR0204*), and he cited a memorandum from the Armed Forces Institute of Pathology that stated "We have come to the conclusion that it is not an acceptable instance of intestinal damage due to radar." This assessment of the report was arrived at after consideration of "many complicating factors" in the case report.

In 1962, McLaughlin (*@MR1061*) described a pattern of capillary fragility, inadequate clot retraction, and abnormal bleeding in workers engaged in the manufacture of microwave equipment (frequencies involved not specified). The author reported finding 115 workers in this facility who showed signs of abnormal capillary fragility. Four representative cases were discussed. The patients' exposures to microwaves had ranged from 1 to 3 h/d for from 6 months to 3 years at distances from an antenna of 0.3-15.2 m. A large area of ecchymosis developed on the hand of one man, aged 39, after a machine shop accident. After he received treatment consisting of bed rest, ice packs, and whole-blood transfusion, he recovered.

In another case described in the same report, a 27-year-old man was examined after complaining of localized tenderness and pain (*@MR1061*). A number of fine dermal red spots were found in the area of pain. After further complaints of malaise, the patient was hospitalized. At this time, his blood pressure was 90/60, and a diagnosis of "stress syndrome" and temporary adrenal insufficiency was made. After being treated with cortisone, the patient recovered. The third case was a woman, aged 26, who had earlier had incidents of persistent bleeding. Ecchymoses developed from her knee to her toes after she bruised her leg on a table. A large hematoma was subsequently evacuated from the injury site, and the wound healed. The last case discussed involved a 28-year-old woman who had complained of malaise and red spots on her arms. The patient was hospitalized after fainting at work, and a tentative diagnosis of subarachnoid hemorrhage was made. All blood studies were normal except "fibrin-clot volume" (further details not given). The patient died 2 weeks after her release from the hospital in spite of a period of apparent improvement. An autopsy showed no aneurysm. Evidence of recent bleeding at the site of the previous hemorrhage was found, however.

Rose et al (*@MR0284*), in 1969, reported the case of a microwave oven repairman who had developed dermal, visual, and genital problems. The individual, a 40-year-old man, had repaired ovens for over 5 years. Measurements showed that while repairing an oven, he was potentially exposed to fields of 10-22 mW/cm^2 of 2.45-GHz radiation, for a minimum of 4 min/exposure, at a distance of 45-90 cm from the oven. His daily involvement with microwave oven repair ranged from zero to almost a full working day. He had developed several episodes of eruption of the skin on the abdomen and thigh. He also complained of a loss of visual acuity and of indurated nodules in his penis that made erection painful and eventually led to impotence. Medical examination revealed no evidence of cataracts or other ocular abnormalities. The patient had a low sperm count, but no direct evidence linked this with his exposure to microwaves. The recurrent skin eruption appeared to arise from vasculitis. Because of the hemorrhagic appearance and anatomic localization of the skin lesions, the authors suggested a possible etiologic role for the patient's microwave exposure in the development of his dermal condition. Similar abnormalities were not seen in seven of the repairman's coworkers with varying amounts of exposure to microwaves.

Doury et al (*@MR2597*), in 1970, described the case of a radar repairman who had been exposed to microwave emissions in the frequency range of

1.3-3.0 GHz for 3 years. The worker exhibited weight loss, tachycardiac episodes, multiple venous thromboses, and endocrine dysfunction. These symptoms reportedly regressed after the patient's exposure to microwaves ended and after treatment with hormones and anticoagulants.

Lethal Effects in Animals

Death in animals from single exposures has been associated with the heating effect of absorption of RF and/or microwave energy. Table III-1 summarizes major studies that described acute lethality in animals exposed to RF and microwave radiation.

Koldaev (*@MR1705*) reported, in 1976, the exposure of groups of 12-16 albino mice weighing 22-26 g to 2.4-GHz radiation at 57-67 mW/cm^2 for 15-16 minutes. Mortality under these conditions was 48-53% during a 3-week observation period. The effect of cholinergic and anticholinergic drugs on survival time was also studied. Some cholinergic drugs, such as pilocarpine or neostigmine, produced an increased rate of survival when they were administered subcutaneously (sc) immediately after exposure. Anticholinergic drugs produced a significant reduction in survival rate. The author concluded that high-intensity microwave radiation damaged the parasympathetic portion of the autonomic nervous system. However, other possibilities are equally likely, such as activation of the sympathetic division of the autonomic nervous

TABLE III-1

LETHALITY IN ANIMALS AFTER SINGLE EXPOSURES TO RADIOFREQUENCY/MICROWAVE RADIATION

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)	Duration (min)*	Remarks	Reference
Mouse (12-16)	2.4	62±5	15-16	47-52% lethality	Koldaev (*@MR1705*)
Mouse	9.1	117-438	10-2	LD_{50} values	Susskind (*@MR1415*)
Mouse (10)	9.27 (PW)	14-58	23	No lethality	Prausnitz and Susskind (*@MR1251*)
"	9.27 (PW)	68-380	18-2	LD_{50} values	"
Mouse	10.0	120-440	Approx 12-2	"	Jacobson and Susskind (*@MR2631*)
"	10.0	5	188	LD_{50} value	Baranski et al (*@MR1402*)
Rat (1-14)	0.95	178-278	4.9-3.1	"	Polson et al (*@MR0134*)
Rat (6)	2.4	150	40.1±1.6	100% lethality	Koldaev (*@MR0893*)
Rat (1-15)	2.45	342-3,920	3.4-0.19	LD_{50} values	Polson et al (*@MR0134*)
Rat (7-14)	3.0	400-2,400	4-0.5	"	Schrot and Hawkins (*@MR0045*), Hawkins et al (*@MR0094*)
Rat (2-35)	4.54	762-12,376	3.2-0.16	"	Polson et al (*@MR0134*)
Rat (4-17)	7.44	629-5,720	3.10-0.28	"	"
Rat (50)	24.0	250	17.4-47	Survival dependent on chamber temperature	Deichmann et al (*@MR0196*)

TABLE III-1 (CONTINUED)

LETHALITY IN ANIMALS AFTER SINGLE EXPOSURES TO RADIOFREQUENCY/MICROWAVE RADIATION

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)	Duration (min)*	Remarks	Reference
Dog (25)	0.2	165-330	7-29 (variable according to exposure orientation)	Lethality dependent on temperature rise and orientation	Addington et al (*@MR2206*)
Dog (10)	2.45	800 (to scalp)	Until death	Mean time to lethality 268 min	Searle et al (*@MR0932*)

*When ranges are given, the higher number corresponds to the lower radiation level (unless otherwise specified).

system and subsequent biologic antagonism between the catecholamines released at sympathetic nerve endings and pilocarpine or neostigmine injected into the animal.

Susskind (*@MR1415*), in 1958, described the lethal effects of 9.1-GHz radiation in mice. Male and female albino mice weighing 30-40 g were restrained in plastic screening and positioned so that they were in a vertical plane facing the power source. Body temperature was measured rectally with a thermistor probe during and after exposure. Power densities of 102-438 mW/cm^2 were found to be lethal. The duration of exposure required was inversely proportional to the power density level. Exposure at 438 mW/cm^2 for 2.3 minutes was equivalent to exposure at 117 mW/cm^2 for 10.2 minutes.

Measurements of rectal temperatures indicated that the incidence of death could be correlated with the maximum body temperature reached (*@MR1415*). A rectal temperature of approximately 44 C (6-7 C above normal) was found at all energy density levels that produced 50% mortality. Survival time of irradiated animals was significantly increased when the mice were pretreated with 6 mg/kg chlorpromazine given intramuscularly (im). This agent lowered body temperature by an average of 10 C. Deaths occurred in these mice only when duration of exposure was sufficient to raise their body temperatures to the critical level. Microscopic examination of sections of the skin, hearts, lungs, livers, and intestines of animals surviving near-lethal exposures revealed hyperemia and cloudy swelling. These changes were especially prominent in the skin. Susskind concluded that the damage observed was similar to that expected from heat injury and that the data suggested that death due to exposure to microwave radiation was not due to radiation per se but to the effects of hyperthermia.

Prausnitz and Susskind (*@MR1251*), in 1962, described acute lethality in mice exposed to pulsed 9.27-GHz radiation (2 μs, 500 pulses per second, or pps) at time-averaged power densities of 14-380 mW/cm^2. The incidence of death was recorded in exposed groups of 10 male Swiss mice (weight unspecified) individually enclosed in a polystyrene restraining device. Measurements of rectal temperature were made during and after irradiation with a thermistor probe. The ambient temperature in the exposure chamber was not stated. Death of 50% of the animals was produced at power densities of 68 mW/cm^2 or greater. The duration of exposure required for mortality was inversely related to power density, with exposure at 68 mW/cm^2 for 17.8 minutes or at 380 mW/cm^2 for 2.3 minutes producing 50% mortality. Power density levels below 58 mW/cm^2 produced no deaths during a 23-minute exposure. Fifty percent of the exposed mice died if their body temperature reached 44.1 C (6.7 C above normal). Power density-related average increases in rectal temperature of 1.3-3.4 C were noted at 14-58 mW/cm^2.

In 1958, Jacobson and Susskind (*@MR2631*) reported the effect of 10-GHz radiation on acute mortality in mice (weight, 35 g). Power densities of 120-440 mW/cm^2 produced 50% mortality; the exposure times required were inversely related to the power density level. An exposure at 440 mW/cm^2 for

2.3 minutes produced the same mortality as an exposure at 120 mW/cm^2 for 11.5 minutes. Power density levels producing lethality induced a 6.7 C average rise in rectal temperature. Exposure at 78 mW/cm^2 for 14.6 minutes did not produce lethality and induced a 4.5 C average increase in rectal temperature. The minimal power density required to produce a rise in rectal temperature was estimated to be 10 mW/cm^2; this power density produced an increase of 0.1 C. Ambient temperature was not stated.

Baranski et al (*@MR1402*), in 1963, reported the results of studies of microwave-induced lethality in mice. Several strains of mice (total of 140 mice) were exposed to PW 10-GHz radiation. Mice of the A_2G strain exposed at 32 mW/cm^2 died in 1-3 minutes. Exposure at 8.6 mW/cm^2 produced death after 33 minutes; this value was considered by the authors to be an LD_{100}. At 5 mW/cm^2, about 50% of the exposed mice died after irradiation for over 3 hours; the authors considered this value to be an LD_{50}. Death of all animals was accompanied by convulsions and was associated with a rectal temperature of 42-45 C. Surviving animals exposed at 5 mW/cm^2 had rectal temperatures of 39 C.

Polson et al (*@MR0134*), in 1974, studied the effects of exposing rats to microwave radiation at 0.95-7.44 GHz. Groups of 1-35 male Sprague-Dawley rats weighing 183-242 g were used. Animals were confined in a Styrofoam restraining apparatus and were positioned facing the microwave source. Observations of mortality were made after 1 hour and 72 hours. Sample measurements of rectal temperature with a thermistor probe were made after exposure at two of the frequencies. No information was provided on ambient temperature during exposure.

Exposure of rats to 0.95-GHz radiation at 278 mW/cm^2 for 3.1 minutes was equivalent to exposure at 178 mW/cm^2 for 4.9 minutes (*@MR0134*). Fifty percent mortality was produced by exposure of rats to 2.45-GHz radiation at 3,920 mW/cm^2 for 0.2 minutes or at 342 mW/cm^2 for 3.4 minutes. A power density of 12,376 mW/cm^2 maintained for 0.2 minutes produced the same percent mortality as that produced in rats exposed to 4.54-GHz radiation at a power density of 762 mW/cm^2 for 3.2 minutes. Fifty percent mortality occurred in rats exposed to 7.44 GHz at 5,720 mW/cm^2 for 0.3 minutes or at 629 mW/cm^2 for 3.1 minutes. The LD_{50} values based on 72-hour mortalities in both these experiments were smaller than those based on 1-hour mortalities. This suggested to Polson et al that some animals suffered damage that was not immediately lethal but from which they were not able to recover, so that they died within the 72-hour observation period.

The principal pathologic finding at all frequencies studied was vascular damage, including edema and hemorrhage (*@MR0134*). Death usually was attributed to asphyxia and pulmonary congestion. The area of damage appeared to move from the lungs toward the nose as the frequency of the microwave energy increased. No relationship was noted between body weight and mortality. A limited number of temperature measurements did not reveal a discernible correlation between rectal temperature and mortality. The authors noted, however, that the experimental animals often felt warmer than normal when handled immediately after exposure. The rats appeared to be more sensitive to radiation at 0.95-2.45 GHz than to that at 4.45-7.44 GHz.

Koldaev (*@MR0893*), in 1970, described the effects of exposing rats to 2.4-GHz radiation. Groups of 6-8 male albino rats weighing 180-200 g were used. Exposure of rats at 150 mW/cm^2 produced death in 6 of 6 animals after 40.1±1.6 minutes. Placement of the animals in an oxygen-rich atmosphere (40%) for 10 minutes prior to irradiation extended survival time by 37%. Exposure of rats to conditions that inhibited cellular oxidation (either by a reduction in the atmospheric oxygen content or by the administration of drugs) decreased survival time by 29-57%. No information was given on rectal or ambient temperatures.

Muroff and Samaras (*@MR1126*), in 1970, reported that survival time after exposure to microwave radiation could be increased through the use of environmental cooling to maintain a constant body temperature. Two 200-g Osborne-Mendel rats were exposed to 2.45-GHz radiation at 100 mW/cm^2. The animals were immobilized in a Lucite restrainer and placed within a Styrofoam-insulated chamber. Rectal temperature was monitored during the experiment with a thermistor probe. The chamber was flushed continuously with air that had been passed through liquid nitrogen. According to the authors, animals not cooled in this manner will die in approximately 14 minutes. Cooling resulted in no deaths after exposure for 60 minutes. No gross abnormalities were noted during a 30-day observation period, and all findings at necropsy were within normal limits. This experiment is not conclusive by itself because it involved only two rats. When considered along with other reports of the involvement of elevated body temperature in microwave-induced lethality, including the protective effect of drug-induced hypothermia (*@MR1415*), this study is significant in showing that prevention of temperature elevation can protect animals from the lethal action of microwave radiation.

Rugh et al (*@MR0376*), in 1976, stated that the lethal effect of microwave radiation is dependent not only on total absorbed dose but also on dose rate and therefore on radiated power. Six groups of male and female adult rats (162 in total) were irradiated until they died in a 2.45-GHz microwave waveguide at forward power levels ranging from 4.83 to 8.56 W. The time to death was inversely related to power level. For example, representative values for time to death in male mice were 44.8±5.4 minutes for a forward power of 5.69 W, which decreased to 7.6±1.2 minutes for a power of 8.56 W.

In 1973, Hawkins et al (*@MR0094*) reported on the frequency and power density dependence of the microwave effect on lethality in the rat. The first study involved 174 adult male rats placed in Styrofoam boxes and exposed head-on to CW 3-GHz radiation until death occurred. The percent mortality was observed to be a linear function of energy density for each of several preselected exposure durations, ie, 0.5, 1, 2, and 4 minutes. Furthermore, the cumulative energy density necessary to produce 50% lethality increased with increasing exposure duration. For example, for 50% lethality, an exposure of 0.5 minute required 1.18 watt minutes (Wmin)/cm^2, whereas an exposure of 4 minutes required 1.67 Wmin/cm^2. The authors attributed this phenomenon to heat loss, conduction, or both. The calculated power densities for 50% lethality were 2.4, 1.2, 0.7, and 0.5 W/cm^2 for 0.5, 1, 2, and 4 minutes, respectively, showing an inverse relationship between power density and exposure duration.

In 1974, Schrot and Hawkins (*@MR0045*) also reported on the lethal effects of 3-GHz radiation in rats. Groups of 7-14 male rats weighing 180-210 g were confined in a Styrofoam restraining enclosure. The animals were exposed to whole-body radiation at power densities ranging from 0.35 to 2.6 W/cm^2 for 0.5-4 minutes. The number of deaths produced by the exposure was recorded. The data supplied by the authors were subjected to regression analysis to determine the power density necessary to produce 50% mortality with 95% confidence limits at each time period studied. The following LD_{50} values were obtained: 2.4 (2.3-2.5) W/cm^2 for 0.5 minutes, 1.2 (1.1-1.3) W/cm^2 for 1 minute, 0.65 (0.6-0.7) W/cm^2 for 2 minutes, and 0.4 (0.38-0.42) W/cm^2 for 4 minutes.

The authors (*@MR0045*) presented data suggesting that rats weighing 195-210 g were more sensitive to the lethal effects of 3-GHz radiation than were rats weighing 180-194 g. Regression analysis of the data indicated that the heavier male rats consistently gave LD_{50} values 6.2-18.5% below those for the lighter ones. The type of data presented did not allow for a determination of the statistical significance of this difference. Schrot and Hawkins noted that the apparent differential toxicity was unexpected, since a smaller body mass is generally more sensitive than a larger one at equivalent microwave frequencies. An examination of the experimental design suggests that the confinement chamber may have contributed to the effects reported. Larger animals may have been at a slight disadvantage for dissipating heat within a constant confined space.

Deichmann et al (*@MR0196*), in 1959, reported the effect of environmental temperature on survival time when rats were exposed to 24-GHz microwave radiation. Groups of 10 female rats were restrained with a plastic holder in a prone position and placed in an absorbent-lined 1,130-liter chamber equipped with a standard horn antenna. The power density used was 250 mW/cm^2. Rectal temperature was monitored with a thermistor probe during and after irradiation. In one set of experiments, an inverse relationship between the temperature within the exposure chamber and the survival time was obtained. Mean survival time was 17.4 minutes at a temperature of 35 C but increased to 47 minutes at 15 C. In other experiments, intermittent exposure to microwave radiation (1 minute on, 3 minutes off) also increased survival time at a rate inversely proportional to environmental temperature. The addition of an air blower to the environmental chamber increased survival time at 15 C from 47 minutes to 14-24 hours. Rectal temperature at death under all conditions ranged from 42.2 to 46.2 C and was essentially independent of environmental temperature.

Lethality in dogs and guinea pigs after exposure to 200 MHz was examined by Addington et al (*@MR2206*) in 1961. A total of 28 dogs was exposed at 38-330 mW/cm^2 for 7-60 minutes. Irradiation was by means of CW energy from a horn antenna in a large anechoic chamber. Mortality was found to depend on elevation of rectal temperature and orientation of the animals relative to the antenna. The lowest doses producing death were 23 minutes at 194 mW/cm^2 (two of seven animals) when the animal was oriented at right angles to the plane of polarization and 18 minutes at 165 mW/cm^2 (one of six animals) when the animal was oriented parallel to the polarization plane. Data on guinea pigs were too inconsistent to detect any trends.

Searle et al (*@MR0932*), in 1959, reported the effects of exposing dogs to 2.45-GHz radiation. Mongrel dogs weighing 11-15 kg were anesthetized and placed in a prone position so that the scalp of each animal was 5 cm from the microwave source. Metallic thermocouples were used to obtain simultaneous temperature measurements from the surface of the scalp, three intracranial sites, and the rectum. Ten dogs were exposed at 800 mW/cm^2 until they died. The mean time to death was 268 minutes (range 150-400). Final rectal temperature (range 42.4-44.4 C) had increased by an average of 6 C (range 4.4-7.1) over preexposure readings (range 36.7-38.6 C) at the time of death. Intracranial and scalp temperatures exceeded 45 C in most cases.

Effects of Short Pulses of Radiation

Short pulses of very high intensity microwave energy are known to be lethal to animals. The most obvious example of this fact is provided by so-called brain inactivation studies with mice and rats (*@MR1744*). Beginning in 1971, numerous reports were published describing the use of 0.2- to 14-second exposures to 2.45-GHz radiation at output powers of 0.6-6 kW for the fixation of brain tissue (*@MR0034,@MR0330,@MR0341,@MR0378,@MR0562,@MR1106,@MR1196, @MR1313, @MR1314, @MR1315, @MR1403, @MR1677, @MR1711,@MR1715,@MR1728,@MR1959, @MR2072,@MR2227,@MR2272,@MR2425,@MR2429,@MR2449*). Brain temperatures of 70-90 C were produced, and mortality was a direct result of microwave irradiation. The goal of most of these studies was to determine the concentrations of neurotransmitters, such as acetylcholine and cyclic adenosine monophosphate (cAMP), in the brain rather than lethality. Examples of the experiments appear in Table III-2. Some of the earlier studies were performed with modified microwave ovens; the later experiments used waveguides to focus the radiation on the animal's head.

None of the studies cited above expressed the exposure conditions in terms of power density (milliwatts per square centimeter) or SAR (milliwatts per gram). Using the fact that waveguides were mentioned as the applicators of the radiation in several papers (*@MR0330,@MR00378,@MR1196,@MR1403,@MR2072*), however, it is possible to calculate a probable value for the size of the exposure area. Schmidt (*@MR0378*) stated that the radiation beam was confined

TABLE III-2

CONDITIONS OF EXPOSURE FOR VARIOUS BRAIN INACTIVATION STUDIES*

Power (kW)	Time of Irradiation (s)	Brain Temperature (C)	Reference
1.1-1.2	1-10	50-85	Stavinoha et al (*@MR1403*)
1.25	1.5	80-85	Schmidt (*@MR0378*)
1.25-5.2	60-2.25	--	Lenox et al (*@MR2072*)
2.5,5.0	0.25-2	35-90	Butcher and Butcher (*@MR1959*)
5.5	0.25,0.4	60-80	Medina et al (*@MR0034*)
6	0.3	75	Merritt et al (*@MR2449*)
6	0.3	90	Modak et al (*@MR0341*)
6	0.3	--	Jones and Stavinoha (*@MR1711*)
6	0.3-3.2	--	Knieriem et al (*@MR1728*)
6	0.2	90	Cheung et al (*@MR1677*)

All experiments performed at a frequency of 2.45 GHz to an area of 4x7 cm, and Lenox et al (@MR2072*) reported that a 5.46x10.92-cm waveguide transmitted the 2.45-GHz radiation to the animal's head. Furthermore, the standard waveguide for radiation in the frequency range of 2.2-3.3 GHz has the dimensions 4.32x8.64 cm. The cross-sectional area calculated for such waveguides is 37.4 cm^2. If it is assumed that all of the power available from the magnetron source is delivered to the animal, ie, that no resistive losses occur during transmission, then output powers of 1.2-6 kW would correspond to incident power densities of approximately $0.3\text{-}2 \times 10^5$ mW/cm^2. These are maximum expected values. Calculated field strengths are as follows:

Power Density (mW/cm^2)	Mean Squared Electric Field Strength (V^2/m^2)	Electric Field Strength (V/m)	Mean Squared Magnetic Field Strength (A^2/m^2)	Magnetic Field Strength (A/m)
0.3×10^5	1.13×10^8	1.06×10^4	796	28.2
2.0×10^5	7.54×10^8	2.75×10^4	5310	72.8

These values signify estimated lethal fluences (doses) for pulses as short as 0.2 second (for 6-kW output power) or 1-1.5 seconds (for 1.1- to 1.25-kW output power). Again, it is difficult to calculate the actual power transmitted to the animal or the incident power density from the information provided in most of the published reports, but Medina et al (*@MR0034*) stated that the 6-kW source they used delivered 5.5 kW at the location of the head. If this relation was true for the remainder of the later reports, then it can be assumed that the output powers and hence the calculated power densities are accurate to within approximately ±10%.

Hemolysis of red blood cells (RBC's) due to an electric field-induced transmembrane potential was reported by Kinosita and Tsong (*@MR3138*) in 1977. A 20-μs exposure of a suspension of human erythrocytes (in an isotonic solution) to a 370 kV/m square-wave pulse was found to increase the permeability of cell membranes to the sodium ion, presumably by creating pores in the membrane. Increasing the osmotic pressure of the suspending solution allowed resealing of the membrane to occur. (Note: A stationary E-field was used in this experiment rather than electromagnetic radiation with a specified frequency.)

Electromagnetic pulse (EMP) radiation consists basically of a traveling pulse of radiofrequency waves accompanied by a nearly instantaneous rise and fall in the associated oscillatory electric and magnetic fields. According to Skidmore and Baum (*@MR1381*), an energy exchange could conceivably occur between the electromagnetic field and a given medium whenever the field is strong enough to alter the kinetic or potential energy of molecules in the medium. However, due to the low average power of EMP radiation, a heating effect would not be expected.

Skidmore and Baum (*@MR1381*), in 1974, published the results of studies designed to determine whether biologic effects could be observed after exposure to EMP radiation. A total of 740 rats and 100 mice was used in experiments in which various biologic assays were performed periodically on exposed and nonexposed animals. The EMP generator that was used emitted 5 pps with a peak E-field intensity of 447 kV/m (5 ns rise time and 550 ns $\frac{1}{e}$ fall time). Exposures totaling 10^8 pulses were continuous over a 38-week period except for approximately 2 h/d, 5 d/wk when biologic sampling and animal care were performed.

No acute injuries were apparent in the exposed animals (*@MR1381*). Some hematologic changes (increased reticulocyte counts and some periods of lowered platelet count) were noted in irradiated rats, but the authors did not judge them to be of functional significance. An analysis of chromosomes in bone marrow cells from exposed rats revealed no increased incidence of chromosomal aberrations as compared with bone marrow cells from control animals.

Twenty female rats were examined for the development of mammary tumors (*@MR1381*). At 1 year of age, no tumors were detected in the irradiated anaimals or in a comparable group of unexposed controls. Five pregnant rats were exposed to $7x10^6$ pulses during 17 days of gestation. Fetuses from exposed and control animals were then removed, fixed, and examined for gross abnormalities. No abnormalities were detected in the fetuses examined. In addition to rats, leukemia-prone mice (42 surviving of an original group of 50) were examined after 33 weeks of EMP exposure ($8.6x10^7$ pulses). No significant differences were noted between the number of leukemic mice in this group and the number in a group of 24 surviving nonirradiated controls (of an original group of 50).

In a later (1976) paper, Baum et al (*@MR3143*) expanded on their earlier report and described the results of experiments in which rats were continuously exposed to a total of 2.5×10^8 pulses of EMP radiation (5 pps/s, 447 kV/m) for 94 weeks. As before, no significant effects of EMP radiation were observed with regard to hematologic variables, chromosomal aberrations, embryology, and tumor formation. The authors concluded that exposure of the animals to EMP radiation presented no biologic hazard to them.

In 1979, Baum (*@MR3139*) reported the results of similar studies in dogs. The EMP radiation characteristics were as before (5 pps/s, 447 kV/m peak intensity, 5 ns rise time and 550 ns i/e fall time). Nine dogs were exposed to EMP radiation, 8 h/d for 45 days, after which time they had received about 5.8×10^6 pulses. Nine sham-irradiated dogs served as controls. As in the experiments with rodents, no significant changes were detected in hematologic variables. Blood samples taken 1 year later were also normal.

Four pregnant female dogs were exposed to EMP radiation between days 10 and 55 of gestation (*@MR3139*). Four unirradiated pregnant dogs served as controls. All pups from the irradiated females were clinically normal and similar in size to pups from the unexposed females. In addition, four exposed male dogs and four nonexposed control dogs were mated with nonexposed female dogs. In all cases, subsequent litters were normal, and there was no indication of differences in mating capabilities among the fathers.

Ocular Effects

Several authors have described the production of ocular effects in humans exposed to RF and microwave radiation. Many of these reports deal with circumstantial evidence; therefore, the etiologic role of microwave energy, although suggested, cannot be proven on the basis of these studies. Table III-3 summarizes the major reports describing ocular changes.

In 1952, Hirsch and Parker (*@MR0820*) reported the case of a 32-year-old male technician who had developed visual impairment after exposure to microwave radiation. The patient had worked for 11-12 months with an experimental microwave generator that had a frequency range of about 1.67-3.33 GHz and an average power output of 100 W (duty cycle = 0.5). Most of the patient's work had been in the lower frequency region. Exposure occurred when power was radiated into a room through a horn antenna. The average power density at which the operator had been exposed daily was estimated to be about 5 mW/cm^2. During the course of his work, the operator reportedly often looked into the antenna, with his face almost in a plane coincident with the antenna rim where the intensity of radiation was calculated to be about 100 mW/cm^2. Shortly after his last exposure, the patient reported an inability to see clearly.

TABLE III-3

OCULAR EFFECTS IN HUMANS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

No. of Cases (Age)	Sex	Frequency (GHz)	Exposure Conditions	Duration	Remarks	Reference
1 (32)	M	1.7-3.3	(1) Average 5 mW/cm^2 (2) 120 mW/cm^2	(1) 1 x d for 11-12 mo (2) 2 h/d for 3 d	Loss in visual acuity; moderate opacities	Hirsch and Parker (*@MR0820*)
1 (22)	M	"Decimeter" (about 0.3-3)	300 mW/cm^2 or more	4-5 times for 2-4 min	Lacrimation, pain, subsequent opacities	Shimkovich and Shilyaev (*@MR1368*)
1 (51)	M	--	Technical writer exposed to microwaves	7 yr	Cataract formation	Kurz and Einaugler (*@MR0234*)
3	M	--	350 mW/cm^2 or more (estimated)	Week to months	Cataract production	Zaret (*@MR1514*)
1 (51)	F	--	Leakage from open oven estimated at 2-40 mW/cm^2 and later at 1-90 mW/cm^2	5 yr or more	"	Zaret (*@MR0058*)
1 (53)	M	--	Radar repairman (at least one "intense" exposure)	27 yr	Blindness; opacities in both eyes	Zaret (*@MR1516*)
9 (35-52)	--	"Hertzian"	Radar technicians, air traffic controllers, and an airline pilot exposed at "non-thermal" levels	Years	Capsular cataracts in radar technicians, air traffic controllers, and an airline pilot	Zaret and Snyder (*@MR1797*)
75	--	--	Diathermy treatment of eyes	--	No damage to lens	Clark (*@MR0531*)
--	--	2.5	"	--	No undesirable ocular effects	Raue (*@MR0372*)

This condition had developed over the previous 7-10 days, apparently following 3 days of increased exposure. During this period, the patient had been exposed with the antenna 10-50 cm from his head for a total of 2 h/d at a level estimated to be as high as 120 mW/cm^2. The authors pointed out, however, that these figures are probably not accurate due to difficulties in measurement.

After the sessions of intense exposure, the man's eyes reportedly appeared "bloodshot" (*@MR0820*). Prior to this time, he had not noticed any visual impairment. Examination showed that the patient's visual acuity had decreased during the 11-12 months of exposure. Further examination revealed a slight roughening of both lenses and moderate nuclear opacities. The authors reported that they had made no attempt to remove the patient's lenses pending clearance of inflammatory changes. Other followup observations were not reported. Hirsch and Parker concluded that this case suggested the need for caution in situations involving exposure to microwaves. However, because of the circumstantial nature of the evidence, they were not prepared to claim that the visual difficulties could definitely be ascribed to microwave exposure.

Cataract formation in a radar technician was described in a 1959 report by Shimkovich and Shilyaev (*@MR1368*). A 22-year-old male operator was exposed four or five times to microwaves in the "decimeter" range (usually interpreted as 300 MHz - 3 GHz) for 2-4 minutes and at power densities of at 300 mW/cm^2. The patient felt his hands get hot during these periods of intense exposure, and shortly after exposure he reported unpleasant ocular sensations, including tearing, eyeball pain, and an abnormal intolerance to light. The patient's visual acuity rapidly deteriorated, and an ophthalmic examination revealed the presence of lens opacities in both eyes. After treatment with iontophoresis (using potassium iodide) and vitamin therapy, no further lens changes were observed. The ocular disturbances were diagnosed as "occupational (ultrahigh frequency) cataracts of both eyes."

Kurz and Einaugler (*@MR0234*), in 1968, reported the development of bilateral cataracts and subsequent extraction of the lenses in a 51-year-old man. Clinical examination before lens extraction revealed dense, centrally located opacities situated below the posterior lens capsule in each eye. The patient had worked for 7 years near microwave and radiowave emitters while employed as a technical writer in an electronics plant. Exposure was not limited to any single frequency, and the patient could not recall ever having looked directly at the source of microwave radiation or radiowaves. The authors concluded that the evidence strongly suggested the involvement of microwaves in producing the observed visual impairment. In view of the limited information on the exposure situation, however, this conclusion is questionable.

Zaret (*@MR1514*), in 1964, cited three cases of cataract formation in men who had been exposed to microwaves at their jobs. Extensive details of these cases were not given. In all three cases, the affected eye was close to the radiating source (either a generating tube or waveguide), and the radiation levels were estimated to be above 350 mW/cm^2. The duration of each exposure was estimated to be several minutes, with exposures occurring from several times per day to several times per week for periods of weeks to months.

In a 1974 paper, Zaret (*@MR0058*) described the appearance of cataracts in a 51-year-old woman who reportedly had been exposed to microwave emissions from a faulty microwave oven. The patient experienced significant loss of visual acuity a few years after installation of a microwave oven in her home. Ophthalmic examination at that time revealed incipient subcapsular opacities in both eyes. A few years later, the patient underwent cataract extraction from the right eye, and subsequent examination of the left eye revealed an advanced capsular cataract. Approximately 5 years after installation of her microwave oven, measurements indicated that the oven leaked at a maximum level of 2 mW/cm^2 during the operation and 40 mW/cm^2 when the door was open. A subsequent test about a year later found leakage levels of 1 mW/cm^2 during operation and 90 mW/cm^2 when the door was open. No indication was given as to how these values were arrived at. Zaret concluded that the patient's inadvertent exposure to microwave radiation (frequency unspecified but presumed to be either 915 MHz or 2.45 GHz) was the cause of her loss of visual acuity and development of cataracts. The patient had originally reported a blurring of her near vision about 5 years before installation of the oven. Although corrective lenses were prescribed, examination at that time had not indicated any anatomic ocular damage.

In 1975, Zaret (*@MR1516*) reported the case of a 53-year-old radar repairman who had developed blindness, deafness, and dizziness after 27 years of working with microwave transmitters. The patient had been involved in at least one accidental exposure to "intense" microwave energy (dose unknown). Ophthalmic examination revealed opacities in the lenses of both eyes. The visual acuities of both eyes were below normal, and the condition for the patient's right eye was diagnosed as an "immature cataract." Since several examining physicians had been unable to determine any specific cause for the patient's blindness, the author concluded that the patient's loss of visual acuity was a result of his long history of exposure to microwave radiation.

Nine cases of cataract formation in workers in operational aviation were described in a 1977 report by Zaret and Snyder (*@MR1797*). The individuals involved were reportedly exposed to "nonthermal" intensities of "hertzian" radiation over a period of years. Three of the patients had been radar technicians aboard electronic-surveillance aircraft; at the time of the original diagnosis of cataracts, their ages were 35, 48, and 35. Five patients had been air traffic controllers; at the time of diagnosis, their ages were 50, 39, 52, 39, and 48. The ninth patient, however, had noticed a loss of visual acuity 3 years earlier and was ultimately disqualified from his job because of deterioration of vision. This last patient, a commercial airline pilot, first noticed a visual disturbance at age 37. Examination 1-2 years later revealed the beginning stages of cataract formation. Subsequently, his loss of visual acuity led to his disqualification for flying. In all nine patients, capsular opacities were found in at least one eye. The authors felt that these opacities resulted from repeated irradiation at "nonthermal" intensities of microwave radiation over a period of years.

In contrast to the reports of microwave-induced ocular damage, therapeutic uses of microwaves have been described without observations of undesirable side effects. In 1963, Raue (*@MR0372*) noted that postoperative or traumatic retinal edema subsided more rapidly if treated with microwaves in the 2.5-GHz range. Raue also described successful treatment of other ocular diseases, but the intensities of exposure that constituted "proper treatment" were not defined.

Clark (*@MR0531*), in 1952, clinically evaluated the results of approximately 75 cases in which microwave diathermy had been used in treating various ophthalmic diseases. The exact dose and frequency of radiation were not specified. However, each treatment consisted of a 15-minute application. The output of the diathermy device was directed at the choroidal region of the eyes, and heat was concentrated in an area of 1-2 inches (sic). While under treatment, patients received various vasodilating drugs. The usual course of therapy consisted of three treatments/wk for 3-6 weeks; occasionally, some patients received a longer course of up to 9 months. The author reported that no damage to the lens had been observed in any of the above cases. Details were given for one case in which a 36-year-old woman received 59 treatments for 9 months. Examination of this patient for up to 9 months after the cessation of treatment showed the lens to be clear and free of any damage. Further followup observations were not reported.

Numerous laboratory studies have shown that under certain conditions ocular changes can occur in animals after exposure to RF and microwave radiation. Most of these studies involve irradiation of rabbits because of the similarities in structure and size between rabbit and human eyes. The diameter of the rabbit eye is about 0.75 that of the human eye.

In many of these experiments, the eye is locally irradiated, an exposure situation quite different from whole-body irradiation. Table III-4 summarizes the major papers discussed in this section.

Early reports indicated that various ocular effects, chiefly cataracts, could be produced in animals by microwaves (*@MR0571,@MR1265,@MR0530*). Daily et al (*@MR0571*), in 1948, briefly described cataract production in dogs after various periods of exposure to microwaves at an unspecified frequency. In the same year, Richardson et al (*@MR1265*) reported experiments showing the production of cataracts in rabbits after exposures to microwave radiation in the frequency range of 2.4-2.5 GHz. Similar results were described by Clark (*@MR0530*), in 1950, for 2.5-GHz radiation.

A 1959 report by Addington et al (*@MR0621*) described a lack of ocular changes in several animal species irradiated with 200-MHz radiation. The

TABLE III-4

OCULAR EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse (several litters)	0.2	50-200 (whole body)	--	No ocular changes	Addington et al (*@MR0621*)
Guinea pig	0.2	220 or 350 (whole body)	60 min/d, 3, 5, or 7 d/wk for up to 45 wk	"	"
Dog (1)	0.2	220 (whole body)	60 min/exposure, 3 exposures/wk for 20 wk	"	"
Sheep (1)	0.2	350 (whole body)	90 min/exposure, 3 exposures/wk for 20 wk	"	"
Rabbit (5)	0.385	60 (horn antenna)	15 min, 2 x wk for 5 wk	"	Cogan et al (*@MR0183*)
Rabbit (4)	0.385	30 (horn antenna)	90 min, 2 x wk for 5 wk	"	"
Rabbit (10)	0.468	60 (estimated) (wave-guide exposure)	20 min, 1 x wk for 5-7 wk	No significant lens changes	"
Rabbit (12)	0.468	"	20 min/d for 10 of 12 d	"	"
Rabbit	0.8-6.3 (CW and/ or PW)	Power output 600-1,000 mW	--	Threshold curves for induction of opacities; no difference between CW and PW; suggestion of frequency dependence	Birenbaum et al (*@MR0444,@MR0445*)
Rabbit (58)	2.45	290-590 (ocular)	90-5 min	Threshold values for cataract production	Williams et al (*@MR1488,@MR2068*)
Rabbit (136)	2.45	120-400 (ocular)	35-3 min	Threshold values for lens opacities	Carpenter et al (*@MR0782*)

TABLE III-4 (CONTINUED)

OCULAR EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit	2.45	120 (ocular)	25 min/d for 5 d; 30 min every other day for 6 d	Production of lens opacities	Carpenter et al (*@MR0782*)
"	2.45	80 (ocular)	60 min/d for 15 d	Lowest chronic level to produce opacities	"
"	2.45 (PW)	80-140 (average)	--	In most cases, time of exposure to produce opacities less than for CW	Carpenter and Van Ummersen (*@MR0396*)
"	2.45	40 (ocular)	60 min/d for 15 d	No opacity production	"
"	2.45	10-12 (from oven)	1 h/d for 12 wk	No cataract production	Bureau of Radiological Health (*@MR1999*)
Rabbit (6)	2.45	250	20 min/d, 5 d/wk for 6 wk	Lens opacities 2 wk after exposure	Williams et al (*@MR0056*)
"	2.45	165	20 min; 2 x d, 5 d/wk, 36 exposures	Ultrastructural lens changes	"
Rabbit (81)	2.45	100-500 (ocular)	1-100 min	Minimum cataractogenic dose 150 mW/cm^2 for 100 min	Guy et al (*@MR0088,@MR1649*)
Rabbit (6)	2.8	160-170 (far field) (ocular)	60 min	Mild conjunctival reactions; 4 developed opacities	Seth and Michaelson (*@MR0292*)
Rabbit (4)	2.8	"	30 min/d for 5 d	No significant lens changes	"
Rabbit (1)	2.8	220-240 (far field) (ocular)	30 min	Slight conjunctival congestion	"
"	2.8	"	45 min	Lens opacities	"

TABLE III-4 (CONTINUED)

OCULAR EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit (3)	2.8	220-240 (far field) (ocular)	60 min	Lens opacities	Seth and Michaelson (*@MR0292*)
Rabbit (1)	2.8	"	10 min/d for 3 d	"	"
Rabbit	3	100-200 (far field)	15 or 30 min	No ocular effect	Appleton et al (*@MR0003*)
"	3	300, 400, or 500 (far field)	15 min	Hyperemia of lids and conjunctiva, engorgement of iris vessels	"
Rabbit (15)	3	50, 100, or 200 (far field)	15 min/d for 30 d	No ocular changes	Hirsch et al (*@MR1658*)
Rabbit (20)	3	300, 400, or 500	"	Iritis, vascular congestion; lens opacities	"
Rabbit (6)	3 (CW)	5	3 h/d for 6 wk	Microscopic lens changes	Tajchert and Chmurko (*@MR1424*)
Rabbit (8)	3 (PW)	5 (average)	"	"	"
Rabbit	5.4-5.5 (CW and PW)	390-790	15-37 min	Acute lens changes leading to cataract formation	Zaret (*@MR1514*)
Rabbit (8)	30	120	Three 35-min exposures; 1 every 2-3 d	Edema, vacuole formation, retinal changes	Balutina and Korobkova (*@MR0845*)
Rabbit (11)	30	5-10	1 h/d for 30 d	Capsular pigmentation, edema, vacuole formation	"
Rabbit (56)	35	Power output 0-600 mW	15-60 min	Corneal injury at 5 mW and above	Rosenthal et al (*@MR3105*)

TABLE III-4 (CONTINUED)

OCULAR EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit (1)	70	Power output 610 mW	30 min	Corneal opacities	Birenbaum et al (*@MR0445*)
"	70	Power output 570 mW	"	No opacities	"
Rabbit (46)	107	Power output 5-60 mW	15-80 min	Corneal injury at 15 mW and above; general recovery by day after irradiation	Rosenthal et al (*@MR3105*)
Dog	2.42	5,000	65 s or more	Lens opacities	Baillie (*@MR0949*)

*Unless otherwise specified

report, however, failed to describe exactly how ocular examinations were conducted. Guinea pigs were exposed at 220 or 350 mW/cm^2 for 60 min/d, 3, 5, or 7 d/wk for up to 45 weeks. Exposures were at either 0.9 or 1.5 m from a helical antenna. A dog was exposed for 60 minutes at 220 mW/cm^2, 1.5 m from the antenna, three times/wk for 20 weeks. A sheep was irradiated for 90 minutes at 350 mW/cm^2, 0.9 m from the antenna, three times/wk for 20 weeks. Several litters of mice were also exposed at intensities of 50-200 mW/cm^2. In all the above species, no ocular changes were observed. Similar negative findings were obtained when a horn antenna was used as a source of 200-MHz radiation, with one possible exception that was apparently due to the presence of a thermocouple in the animal's eye.

Cogan et al (*@MR0183*), in 1958, did not find cataract production in experiments with adult male rabbits subjected to whole-body microwave radiation. Animals were irradiated by either a waveguide (468 MHz) or by a horn radiator (385 MHz). Test animals irradiated by the horn antenna were contained in a Lucite box. However, the distance of the animals from the antenna was not specified. Ten rabbits in one group received 20-minute waveguide exposures (estimated at 60 mW/cm^2) once weekly for 5-7 weeks. Twelve other rabbits were irradiated by waveguide daily (20 minutes at 60 mW/cm^2), except for 2 days, for a total of 10 exposures. From measurements made on the animals in these groups, the average power absorbed was estimated to be 8.1±1.25 W/kg. Of the animals irradiated with the horn antenna, the authors estimated that, for each exposure, five rabbits received 60 mW/cm^2 for 15 minutes and four were exposed at 30 mW/cm^2 for 90 minutes. A total of 10 exposures was given at the rate of 2 exposures/wk. Cogan et al observed no cataract formation in any of these exposure situations. Although some lenticular opacities were occasionally seen, these were also observed in control animals and were considered insignificant.

Daily et al (*@MR0573,@MR0572*), in 1950 and 1952, described cataract production in dogs and rabbits after repeated exposures to microwave radiation at 2.45 GHz. Dogs were irradiated 30 min/d, for 1-10 days, by means of a corner reflector connected to a microwave generator with a power output of 94-122 W. The distance from the eyes to the radiation source was 3.8-12.7 cm. Ocular changes were observed in four of eight anesthetized dogs, two of which subsequently developed cataracts. Rabbits were exposed under similar conditions at various distances from the source and for various periods of time. Detailed dosimetric information was not given.

A 1952 report by Richardson et al (*@MR1270*) showed that microwave-induced cataract formation was related to the distance of the eyes from the power source. Rabbit eyes were irradiated with a 2.45-GHz rectangular wave-guide (aligned directly on, and at right angles to, the optic axis). Animals were anesthetized, and in some cases pupils were dilated by topically applied chemical agents. Power output was 100 W, but power density levels were not reported. In 12 of 14 cases, animals irradiated for 15-25 minutes at distances of 3-3.8 cm from the power source developed lenticular opacities within

1-14 days. However, of six animals irradiated at 5 cm for 17-25 minutes, only one developed an opacity. No opacities developed in 11 animals exposed for 20 minutes at 15.3 cm. Thirty-three percent of animals suffering from alloxan-induced diabetes developed opacities in the irradiated eye 2-15 days after exposure at a dose that, according to the authors, had previously been found to be undamaging to the eyes of normal rabbits.

Birenbaum et al (*@MR0444,@MR0445*), in 1969, described acute ocular effects in anesthetized rabbits exposed to microwave radiation at various frequencies. Animals were exposed to 0.8, 4.2, 4.6, 5.2, 5.4, 5.5, and 6.3 GHz with CW and/or pulsed power (0.001 duty cycle) from either a waveguide or a coaxial adaptor. Power levels were between 600 and 1,000 mW (power densities not given). Acute inflammation of the cornea, conjunctiva, iris, and/or ciliary body was observed in most animals. The inflammation, however, usually subsided by the 4th day after exposure. Threshold curves of average power vs time of exposure were constructed for analysis of the induction of lens opacification. In such cases, opacification was usually apparent by the 4th day after exposure. No significant differences were observed between threshold curves for CW and PW, indicating that, under the conditions of this study, average rather than peak power determines whether lens injury will occur. Essentially all the observed opacification occurred in the anterior section of the lens. At an average power level of 1 W, the results suggested that, for the frequencies used (between 0.8 and 6.3 GHz), the efficiency of induction of lenticular opacities decreased as frequency decreased.

A small rectangular horn (1.0x0.7 cm) was used as the applicator in preliminary experiments by Birenbaum et al (*@MR0445*) with CW 70-GHz exposures. Clearance between the horn edge and the eye was about 0.8 mm. Diffuse corneal opacification was observed after one 30-minute exposure at 610 mW. However, no effect was seen at this frequency after a 30-minute exposure at 570 mW, suggesting that a threshold intensity exists for the induction of corneal opacity by radiation at this frequency and within this time period. The limited results of these and other exposures near 600 mW indicated that the most severe injury occurred near the corneal surface at this frequency.

Williams et al (*@MR1488,@MR2068*), in 1955, reported the results of experiments designed to measure cataractogenic thresholds of microwave irradiation. The right eyes of anesthetized male rabbits were exposed 5 cm from a source of 2.45-GHz radiation, the left eyes serving as controls. Animals were irradiated 3.5-8 minutes at 590 mW/cm^2 and 90 minutes at 240 mW/cm^2. Periodic examinations of both eyes were performed for at least 90 days (and occasionally for up to 6 months) after single exposures. Opacities developed in the right eyes of 32 of 58 irradiated rabbits. No opacities were detected in eyes of the controls. A curve of threshold incident power density vs duration of exposure was prepared from the data. Threshold values ranged from about 5 minutes at 590 mW/cm^2 to about 90 minutes at 290 mW/cm^2.

Carpenter et al (*@MR0782*), in 1960, reported the results of studies on microwave-induced ocular effects in rabbits. A total of 136 anesthetized rabbits was exposed to single doses of CW 2.45-GHz microwave radiation at various intensities and for various lengths of time in an anechoic chamber. During irradiation, the corneal surface of each animal's right eye, which was 5.1 cm from the surface of the housing covering the antenna, was positioned opposite the dipole crossover of an antenna used as the source of microwaves. The left eye served as a control. Power density measurements were made calorimetrically, and the authors were careful to point out that they did not consider these to be exact measurements.

From the results of the single-exposure experiments, a curve was constructed to give minimal exposure periods required to produce lens opacities at each power density level (*@MR0782*). For example, a 35-minute exposure was required to produce an opacity at 120 mW/cm^2, whereas only about a 3-minute exposure at 400 mW/cm^2 was required to induce a lenticular opacity. The opacities, which were in the posterior subcapsular cortex of the lens, appeared 1-6 days after irradiation. Some immediate ocular reactions were observed after irradiation, but these were minor and transitory at power density levels of 280 mW/cm^2 or below.

Carpenter et al (*@MR0782*) also designed experiments to test the cumulative effect of repeated exposures at times less than the minimum required for the production of an opacity. The results of these irradiations showed that opacities could be produced under certain subthreshold conditions. For example, a 25-minute exposure at 120 $mW/cm^2/d$ for 5 days or a 30-minute exposure at 120 mW/cm^2 every other day for 6 days produced lenticular opacities, even though the single-exposure threshold was 35 minutes at this level. The lowest power density level that gave a positive result in this series of experiments was 80 mW/cm^2; at this level, daily 60-minute exposures given for 15 consecutive days resulted in opacities in each of three experiments.

Pulsed microwave power at 2.45 GHz was used to irradiate the right eyes of rabbits at average power densities of 40-140 mW/cm^2 (*@MR0782*). In more than half of the 37 experiments in this series, lens opacities were produced at periods of PW exposure significantly less than those required to produce opacities by CW radiation at equal power density levels. The authors concluded that peak power density, rather than average power density, may be the most important factor when the eyes are exposed to pulsed microwave radiation.

In a 1968 paper, Carpenter and Van Ummersen (*@MR0396*) described more extensive work on the ocular effects of microwaves on rabbit eyes. Exposure conditions were the same as in the earlier study (*@MR0782*). Single 60-minute exposures to 2.45-GHz radiation at either 40 mW/cm^2 or 80 mW/cm^2 did not produce lens opacities. Also, daily 60-minute exposures at 40 mW/cm^2 given for 15 consecutive days did not result in the production of any lenticular opacities in two experiments. However, as reported previously (*@MR0782*), repeated 60-minute exposures at 80 mW/cm^2 could induce the formation of cataracts.

Experiments at 8.24 and 10.05 GHz were also performed as part of these studies (*@MR0396*). A "closed waveguide" exposure system was used. Although cataractogenic threshold levels could be established, this type of exposure system did not allow measurement of power density levels. Other experiments were conducted in which rabbits were exposed in an anechoic chamber to 10.16-GHz far-field radiation generated by a horn antenna; however, field perturbations caused by the animals prevented the establishment of a uniform exposure situation.

Williams and Finch (*@MR0055*), in 1974, described the irradiation of unanesthetized rabbits for 20-30 min/d with 2.45-GHz CW or 2.86-GHz pulsed microwave radiation at an average power density of 225 mW/cm^2 for up to 5 weeks. Autoradiography revealed no detectable effect on the uptake of radioactively labeled thymidine by corneal cells (a measure of DNA synthesis). In a 1975 report, however, Williams et al (*@MR0056*) reported ultrastructural changes in the lens after microwave irradiation at 2.45 GHz. Six rabbits received 250 mW/cm^2, 20 min/d, 5 d/wk for 6 weeks. Another six received 165 mW/cm^2, 20 minutes twice daily, 5 d/wk for a total of 36 exposures. Animals in the first group were killed 2 weeks after the last exposure, and all had lens opacities detectable by slit lamp examination. Animals in the second group were killed 5 days after the last exposure. Although the lenses of these animals appeared normal on slit lamp examination, subsequent examination by electron microscopy revealed extensive morphologic changes, including enlarged fibers in the posterior subcapsular cortex, intracellular cystoid spaces, and intercellular clefts.

Experiments by Kramar et al (*@MR0233*), in 1975, indicated that a temperature increase following microwave irradiation is necessary for the production of cataracts in rabbits. Eighteen rabbits were irradiated with 2.45-GHz microwaves at power densities determined by the authors to be cataractogenic. When the temperature of the eyes was not allowed to exceed 41 C (by general hypothermia), none of the animals developed cataracts.

Guy et al (*@MR0088,@MR1649*), in 1974 and 1975, reported studies with rabbits to determine cataractogenic threshold doses of microwaves. A total of 81 rabbits was used in the study. They were sedated, and their pupils were dilated before irradiation. The animals were placed in an anechoic chamber; the right eyes were irradiated with near-zone 2.45-GHz microwaves generated by a corner reflector with horizontal polarization. The left eyes served as controls. Some immediate transient postirradiation effects, such as tearing and pupillary constriction, which depended on the intensity of exposure, were noted. At low exposure levels, mild and often reversible banding was observed in the lenses. At higher levels of irradiation, more pronounced and permanent lenticular changes were observed. Lenticular alterations usually appeared 1-2 days after irradiation. From the data obtained after irradiation at levels between 100 and 500 mW/cm^2 for 1-100 minutes, the minimum cataractogenic dose at 2.45 GHz under these conditions was determined to be 150 mW/cm^2 for 100 minutes. This figure represented a maximum absorbed power of 138 W/kg.

A 1978 report (*@MR1999*) from the Division of Biological Effects, BRH, described the results of studies on rabbits exposed to low-level radiation from microwave ovens. Rabbits were placed in front of a microwave oven that had been adjusted to leak radiation (presumably at 2.45 GHz) at an intensity of 10-12 mW/cm^2. After daily 1-hour exposures for 12 weeks, the rabbits' eyes showed no indications of cataract formation. Further details were not given.

Van Ummersen and Cogan (*@MR0312*), in 1965, examined the effect of age in microwave-induced cataractogenesis. A total of 163 anesthetized rabbits (aged 5 weeks to more than 1 year) received doses to the right eyes above and below a previously determined cataractogenic level at a frequency of 2.45 GHz (power density not specified). The exact number of animals showing ocular effects was not clear from the data presented. However, 70-100% of those animals receiving exposures above the cataractogenic level (8 minutes' irradiation, 5.1 cm from a dipole antenna) showed some degree of ocular effect, ranging from a thickening of the posterior suture line to circumscribed or diffuse cataracts. The latter required several days to develop fully. No correlation was seen between the ages of the animals and their susceptibility to lens damage.

In a 1976 study, Van Ummersen and Cogan (*@MR1471*) followed the time course of lens changes in rabbits after cataractogenic exposures to 2.45-GHz radiation. The results suggested that metabolic changes in the lens following exposure might be the result of hydration of lens epithelial tissue.

Seth and Michaelson (*@MR0292*), in 1965, reported the results of studies on microwave-induced lenticular changes in 3- to 4-month-old rabbits. The left eyes of unanesthetized animals were irradiated at 2.8 GHz under far-field exposure conditions. The unexposed right eyes served as controls. Animals were irradiated in a restraint box with an outer layer of microwave-absorbing material. Eyes were examined before exposure and for up to 6 months after exposure. Sixty-minute exposures at 220-240 mW/cm^2 resulted in the development of lenticular opacification in each of three animals tested. An animal exposed for 45 minutes at this power density level and another exposed for 10 min/d for 3 days also developed lenticular opacities. A single 30-minute exposure at this level produced only slight conjunctival congestion in a third animal.

In general, exposure at lower power density levels produced transient and less severe effects, if any (*@MR0292*). Six rabbits exposed at 160-170 mW/cm^2 for 60 minutes showed mild conjunctival reactions. Three of these animals also developed lenticular opacities that were, for the most part, transitory in nature. A small opacity in a fourth animal remained stable after 3 months. Four rabbits exposed at 160-170 mW/cm^2 for 30 min/d for 5 days showed no lenticular changes after 3 months except for a transient blackening of the lens in one animal.

Appleton et al (*@MR0003*), as reported in 1975, exposed rabbits at various power density levels of 3-GHz CW radiation in the far field of a focusing dish antenna. The animals were anesthetized and placed on a Styrofoam platform in an anechoic chamber with their left eyes on the beam axis. Field intensities were monitored by an electromagnetic radiation meter and probe. No ocular effects were observed in those animals receiving 100 or 200 mW/cm^2 for 15 or 30 minutes. However, during 15-minute exposures at 300, 400, or 500 mW/cm^2, animals developed acute changes in and around their eyes that persisted for up to 24 hours. These changes included hyperemia of lids and conjunctivae and engorgement of iridial vessels. No lenticular changes or cataracts were observed in these animals during followup observations.

In a 1977 report, Hirsch et al (*@MR1658*) described the results of chronic 3-GHz irradiation of the eyes of 35 albino rabbits. The left eyes of the animals were irradiated during 15 min/d for a total of 30 consecutive days at power densities of 50, 100, 200, 300, 400, or 500 mW/cm^2. Exposure techniques were the same as those in the above study by Appleton et al (*@MR0003*). At the higher power densities, fewer animals survived the 30-day exposure period (*@MR1658*). Periodic examinations of the eyes of surviving animals were made during and after the exposure period. Lenses from some rabbits were sectioned, and the sections were stained and examined microscopically. No ocular changes were detected in animals exposed to power densities below 300 mW/cm^2. All animals exposed at or above 300 mW/cm^2 developed acute ocular changes, including iritis, pupillary constriction, and congestion of the limbal vessels. Posterior subcapsular iridescence also developed after exposure at 300 mW/cm^2 or more. The lenticular opacities progressed during a subsequent 1-year period of observation.

A 1972 report by Tajchert and Chmurko (*@MR1424*) described the production of microscopic changes in the lenses of rabbits exposed to 3-GHz radiation at relatively low power density levels. A total of 14 animals was irradiated (exposure details not given). Six rabbits were exposed to CW radiation, and eight were exposed to PW radiation (duty cycle not specified). In all cases, the average power density was reportedly 5 mW/cm^2, and all animals were exposed for 3 h/d for 6 weeks (total of 124 hours). Three rabbits served as controls.

Ocular examinations were made periodically during and after exposure (*@MR1424*). Macroscopic lens changes were not observed in irradiated animals. However, histologic preparations of lens tissue from exposed rabbits revealed certain alterations, including thickening of the anterior capsule, changes in the growth of the capsular membrane, obliteration of prism structures, and the presence of necrotic foci near the nucleus of the lens. The authors noted that these changes could be regarded as early signs of cataract formation.

Acute ocular effects were reported by Zaret (*@MR1514*), in 1964, after irradiation of the eyes of anesthetized rabbits with high levels of 5.4- to 5.5-GHz microwaves produced in a closed waveguide system. Exposures below

100 mW/cm^2 to either PW or CW radiation for 60 minutes did not produce acute lens injury. However, both CW and PW (200 pps, 0.001 duty cycle, 5-μs pulse length) radiation at average power densities of 390-790 mW/cm^2 and exposures of 15-37 minutes resulted in acute lens changes that led to cataract formation.

In 1956, Belova and Gordon (*@MR0775*) observed acute and chronic eye effects after rabbits had been irradiated with 3-GHz microwaves. Animals were irradiated in a metal box that had an aperture for a wire gauze headpiece with an opening for one eye. Pupils were dilated before irradiation, and the eyelids were kept open by taping. In one experimental series, rabbits (exact number not specified) were irradiated with 110 mV/cm^2 (sic) for one to seven 60-minute exposures. No information was provided by the authors as to the importance of the number of these exposures in producing ocular effects. The immediate effects appeared to be transitory and included reddening of the conjunctiva, injection of pericorneal vessels, and hyperemia. Some animals reportedly also developed some lenticular banding. In a second experimental series, rabbits (exact number not specified) were exposed at 110 mV/cm^2 (sic) for 10 min/d for 6 weeks. Lenticular bands of opacity reportedly developed in at least some of these animals after 15-17 exposures (21 days). Because of the lack of quantitation, however, the extent of the radiation effects noted could not be determined.

Effects of 10-GHz pulsed microwaves on rabbit eyes were studied by Richardson et al (*@MR1267*) in 1951. Animals were anesthetized and irradiated on a polystyrene pedestal on a wooden table, and vasodilatory drugs were applied to the eyes prior to exposure. Right eyes were exposed in all cases, with the left eyes serving as controls. The radiation source was a PW microwave generator that delivered an average power output of 34-67 W with a duty cycle of 0.001 (power densities not specified). The wave director was aligned directly on, and at a right angle to, the optic axis, with the cornea positioned 5 cm from the director cone. Twelve rabbits were exposed at an average output of 67 W for 3-5 minutes. Nine of these animals developed corneal opacities, and four exhibited anterior lenticular opacities; six cases of extraorbital burns on the eyelids or facial area were observed. Three animals had no burns. A second group of nine rabbits was exposed at 34-50 W for 10-25 minutes. Seven of these animals developed corneal opacities, three had anterior lenticular opacities, and four developed extraorbital damage. No damage was observed in two animals.

Balutina (*@MR0844*), in 1965, subjected the eyes of 20 rabbits to radiation in the 30-GHz range at 120 mW/cm^2 for 20-50 minutes. The animals were reportedly irradiated 69 times on a stand designed to prevent head movement. The eyelids of the animals were ligated open, and the bodies of the animals were shielded from microwave energy by a protective fabric. Further exposure details were not given. During irradiation, the surface temperature of the eyes was found to increase by 2-5 C. The authors did not observe the formation of new lens opacities in irradiated animals, but they did note that previously existing congenital cataracts worsened in nine animals.

In a 1969 paper, Balutina and Korobkova (*@MR0845*) described the production of histologic changes in the eyes of rabbits exposed to radiation in the 30-GHz range (exposure details not given). In the first experimental series, eight rabbits received 35-minute exposures at 120 mW/cm^2. Three exposures were given, each separated by 2-3 days. Clinical changes (details not specified) were observed in three of the eight rabbits. Also observed were certain histologic alterations, including limited edema, vacuole formation, and retinal changes. In the second experimental series, rabbits received daily 1-hour exposures at 10 mW/cm^2 or 5 mW/cm^2 for 30 days. Although no clinical changes were observed, some histologic alterations were reported, including capsular pigmentation, limited fiber edema, and vacuole formation.

Rosenthal et al (*@MR3105*), in 1976, reported the results of exposing the eyes of anesthetized rabbits to 35- or 107-GHz radiation for periods ranging from 15 to 80 minutes. Corneal damage, as measured by a slit lamp, was graded after irradiation at power output levels of 0-600 mW, although most experiments were carried out below 50 mW (incident doses were not given). For 35-GHz irradiation, the lowest power output at which injury occurred was 5 mW, whereas for 107-GHz radiation, this level was 15 mW. Although 107-GHz radiation was more effective than 35-GHz radiation in producing immediate injury, the damage generally disappeared by the next day. The effects seen after 35-GHz irradiation were more persistent and were associated with high levels of epithelial injury.

A 1970 report by Baillie (*@MR0949*) suggested that microwave-induced cataracts in dogs were due to thermal coagulation of lens proteins. Exposures were made into the cornea of the right eye of each animal from a hole that permitted leakage of a microwave field into an aluminum exposure cavity. The animals were under general anesthesia, and both eyes were dilated. Eyes were secured by sutures to a plate around the hole, and the left eyes served as controls. Exposure at about 2.42 GHz and 5 W/cm^2 (measured calorimetrically) for 65 seconds or more produced lenticular opacities of various degrees at times ranging from immediately to 7 days after irradiation. These opacities generally were patchy and evenly distributed throughout the cortical area of the lens. Exposures made under hypothermic conditions (immersion in ice water) did not produce cataracts.

In addition to reports of microwave-induced cataract formation, other ocular effects have been described after microwave irradiation. Daily et al (*@MR0570*), in 1951, observed a postirradiation reduction in the activities of certain enzymes found in lens tissue, and, in 1966, Kinoshita et al (*@MR1683*) reported a decrease in the level of ascorbic acid in animal lens tissue after exposure to microwave radiation.

In 1972, Grechuskina (*@MR0925*) described cataract formation in 23 of 28 rabbits after the left eyes had been irradiated with 2.38-GHz microwaves. The formation of these opacities was correlated with decreases in the concentrations of ascorbic acid and thiol in the crystalline lenses. Power output of the source used was 60 W, and animals were exposed 10-14 times for 15 minutes each. Further dosimetry information was not given.

Effects on the Neuroendocrine System

Limited data regarding the effects of RF and microwave radiation on the neuroendocrine system have been obtained in the few human studies reviewed (Table III-5). Epidemiologic studies have provided additional information on neuroendocrine effects (*@MR0739,@MR0873,@MR1835*). Table III-6 summarizes the variety of effects produced on the neuroendocrine system of animals by RF and microwave irradiation. General Physiologic and Other Effects includes reports that give further data. Most of the reports mention changes in neuroendocrine gland weight (*@MR2664*) or secretion of neuroendocrines (*@MR2383*). These changes were found to be temporary and, for the most part, were correlated with the response of the various functional axes of the neuroendocrine system to thermal stress (*@MR1601*).

(a) Ultrastructure and Secretory Function

Leites and Skurikhina (*@MR1194*), in 1961, observed a small transient decrease in the concentration of ascorbic acid granules and of lipoid bodies within the adrenal cortices of rats following a single exposure to 2.38-GHz microwave radiation. Both concentrations decreased simultaneously by

TABLE III-5

NEUROENDOCRINE EFFECTS IN HUMANS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Number of Cases (Age Range)	Frequency	Exposure Conditions	Duration	Remarks	Reference
38	"SHF"	--	24-1,800 h	No changes in 17-ketosteroid and 17-corticosteroid levels and in Na:K ratio	Afanas'yev (*@MR0417*)
20 (30-46)	"	--	10-20 yr	Decrease in adrenal secretion of tetrahydro-cortisone and cortisone	Dumkin and Korenevskaya (*@MR2629*)
(12) ("Young")	"Radar" (PW)	0.2-6 mW/cm^2	--	No changes in 17-hydroxy-corticoid and 17-keto-steroid levels	Szady et al (*@MR0383*)

TABLE III-6

NEUROENDOCRINE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse	2.5	62	11 min	Depletion of neuroendocrines inferred	Koldaev (*@MR0025*)
Rat (199 total)	0.01488	70 V/m	Unspecified daily exposure for 1-8 mo	Decrease in thyroid and adrenal gland weight	Demokidova (*@MR2654*)
"	0.0697	5, 12, 48 V/m	1 h/d for 1.5 mo	Increase in adrenal and pituitary gland weight, decrease in thyroid gland weight at 4 h/d	"
Rat (108 total)	3	0.153 mWh/cm^2	1-2 h	Decrease in adrenal and pituitary gland weight, increase in thyroid gland weight	Demokidova (*@MR2664*)
Rat (620)	0.0571	600 W (near-field conditions)	5, 15, 30 min	Significant decrease in ascorbic acid content of adrenal glands; radiant heating (IR) produced similar effects	Adler and Magora (*@MR2010*)
Rat (20)	2.375	50 W	10 min	Transient decrease in ascorbic acid and lipids in adrenal cortex	Leites and Skurikhina (*@MR1194*)
Rat (891)	2.38	(1) 0.01, 0.1, 1, 10, 75 mW/cm^2 (horizontal polarization)	(1) 30 min	(1) Power density-dependent increases up to 1 mW/cm^2 in corticotropin-releasing factor activity in hypothalamus in pituitary adrenocorticotropic hormone activity, and in concentration of 11-oxycorticosteroids and the Na:K ratio in the blood	Novitski'i et al (*@MR0307*)

TABLE III-6 (CONTINUED)

NEUROENDOCRINE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat (891)	2.38	(2) 1 mW/cm^2 (horizontal polarization)	(2) 30 min/d for 10, 20, or 30 d	(2) Increases in indices noted above progressively declined from maximum at 10 d to below control values at 30 d	
Mouse	2.5	62	11 min	Depletion of neuroendocrines inferred	Koldaev (*@MR0025*)
"	46.2	1	15 min/d for 20 d	Increase in 17-oxycorticosteroids in blood, decrease in ascorbic acid in adrenals; adrenaline increased in blood, hypothalamus, and adrenals; noradrenaline decreased in hypothalamus, increased in blood and adrenals	Zalyubovskaya and Kiselev (*@MR3066*)
Rat	"Microwave"	20,000, 40,000, 60,000	10 min	Transient increase in plasma glucose; decrease in adrenal ascorbic acid content at 40 and 60 W/cm^2	Todorovic et al (*@MR2161*)
Rat (86)	2.45	1-20	1-8 h	No change in adrenal, thyroid, or body weight; depression of corticosterone and thyroxine levels after 20 mW/cm^2 for 4 or 8 h	Lu et al (*@MR1989*)
Rat (18)	2.45	40	5 min/d for 6 d	Increase in adrenal gland weight, plasma corticosterone levels unchanged, response to adrenocorticotropin enhanced	Guillet and Michaelson (*@MR2000*)
Rat	2.45	13-60	30-120 min	Increase in corticosterone level related to exposure	Lotz (*@MR0113*), Lotz and Michaelson (*@MR1704*)

TABLE III-6 (CONTINUED)

NEUROENDOCRINE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	2.45	10-25	4 and 16 h	No change in adrenal or plasma cortisone level or adrenal weight; decrease in adrenal epinephrine level after 16 h at 10 mW/cm^2; no change in serum protein-bound iodine, serum thyroxine, or iodine uptake by thyroid	Parker (*@MR0038*)
"	2.45	15	60 h	Decrease in iodine uptake, bound iodine, and thyroxine level	"
Rat (16)	2.45	100	10-40 min	No change in iodine uptake, tetra or triiodothyronine secretion, TSH, or hypothalamic thyrotropin releasing factor level; no histologic changes in thyroid	Milroy and Michaelson (*@MR0264*)
Rat (10)	2.45	10	8 h/d for 56 d	"	"
"	2.45	1	56 d	"	"
Rat (15)	IR	--	10-40 min	"	"
Rat and dog	2.45 (frequency modulated)	(1) 13-60 (2) 13-40 (local and whole-body exposure)	(1) 30, 60 min (2) 120 min	Increased secretion of thyroxine and T_3 from thyroid and of corticosterone from adrenal related to generalized reaction of HHA axis to stress (thermal); threshold for effect at 20-30 mW/cm^2	Michaelson et al (*@MR1718*)
Rat (400)	2.45	9-36	2.5 h	Decrease in growth hormone level after 60 min at 36 mW/cm^2	Houk and Michaelson (*@MR0836*)

TABLE III-6 (CONTINUED)

NEUROENDOCRINE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	2.87	10	15 and 30 min	No change in corticosterone level	Mikolajczyk (*@MR1890*)
"	2.87	5 and 10	2 h/d for 35 d	No change in corticosterone and growth hormone levels	"
"	2.88	15	2 min/d for 43 d	Ultrastructural changes in pineal gland (increased secretion)	Cieciura et al (*@MR0524*)
Rat (160)	24	250 (to scrotum; far field)	5-15 min	Temporary decrease (at 12-15 d) in prostate weight and zinc uptake	Gunn et al (*@MR0210*)
Rat	37.5-60	1	15 min/d for 60 d	Decrease in 17-oxycorticosteroids in blood and ascorbic acid in adrenals; increase in adrenaline and decrease in noradrenaline levels in hypothalamus and adrenals	Zalyubovskaya (*@MR0749*)
Guinea pig (33) and rat (25)	2.375	(1) 7 (2) 18	(1) 15 min/d for 6 d (2) 15 min/d for 10 d	Progressive increase in urinary excretion of 17-oxycorticosteroids, adrenaline, and noradrenaline during first 3 d of irradiation	Kardashev and Gersamiia (*@MR2383*)
Rat (140) and rabbit (30)	0.05	0.5-6 V/m	10-12 h/d for 180 d	Increase in urinary excretion of 17-ketosteroids	Serdiuk (*@MR2518*)
Rat (228) and rabbit (60)	(1) 0.050 (CW) (2) 2.5 (CW)	(1) 0.0006-10 (u)W/cm^2 (2) 0.5-10 (u)W/cm^2	(1) 10-12 h for 120 d (2) 8 h for 120 d	Power densities of 1.9-10 (u)W/cm^2 (case 1) and of 5-10 (u)W/cm^2 (case 2) increased urinary excretion of 17-ketosteroids and adrenal gland weight but decreased adrenal ascorbic acid content.	Dumanskii and Shandala (*@MR1832*)

TABLE III-6 (CONTINUED)

NEUROENDOCRINE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit (70)	0.46	110, 330 (irradiation localized to back in the region of adrenals)	6 min/d for 12 d	Stimulation (lasting 20 d) of pituitary-adrenocorticoid system at 110 mW/cm^2 resulted in increased levels of 11-oxycorticosteroids in blood, epinephrine in adrenals and hypothalamus, norepinephrine in blood, adrenals, hypothalamus, and heart, and DOPA in hypothalamus.	Grigor'eva et al (*@MR2320*)
Rabbit (45)	3.0	110, 380 (localized to back in the adrenal gland region)	6 min/d for 12 d	Decrease in adrenaline concentration in adrenals and noradrenaline in heart, blood, and hypothalamus, indicating inhibition of hormone formation in adrenal cortex and of sympathetic-adrenal system	Maksimova (*@MR2437*)
Rabbit (10)	3	5	3 h/d for 4 mo	Increase in iodine uptake and thyroid secretion	Baranski et al (*@MR0852*)
Dog	2.45	72, 162, and 236	2 h	Thyroid gland temperature maintained at 38.5, 41, or 45 C, respectively; secretion increased with length of exposure; no histologic or ultrastructural changes noted	Magin et al (*@MR0115, @MR1710*)

Power density unless otherwise specified approximately 25% within 24 hours after irradiation for 10 minutes. The decline was followed by a progressive increase to control levels, attained within 2 days after irradiation and maintained for 14 days postexposure. Rats irradiated in the adrenal region with microwaves (frequency between 3 and 30 GHz) at high power densities showed increased adrenal gland function, according to a 1965 report by Todorovic et al (@MR2161*). Ten minutes of irradiation at 20 W/cm^2 produced a 10% increase in blood sugar 2 hours postirradiation but no change in the ascorbic acid content of the adrenal glands. This hyperglycemia was attributed to increased release of adrenaline following heat stress. Decreases in ascorbic acid content observed following irradiation at the higher power densities were interpreted as being due to a stimulation of secretion of corticosteroids by the adrenals.

Adler and Magora (*@MR2010*), in 1964, reported that radiant heat, ie, infrared (IR) radiation, and 57-MHz radiofrequency radiation produced similar statistically significant decreases in the ascorbic acid content of the adrenal gland of the rat. The results indicated that deeply penetrating radiation (RF) and radiation with effects limited to the skin (IR) produce similar thermal effects on the adrenal gland. Results reported by Dumanskii and Shandala (*@MR1832*) supported these findings.

In 1969, Cieciura et al (*@MR0524*) described only slight changes in the ultrastructure of pineal gland cells of rats after long-term microwave irradiation. The rats were exposed at 15 mW/cm^2 for 2 min/d to CW 2.88-GHz radiation for a total of 43 days. Electron micrographs showed increased waviness in the nuclear membrane and an enlarged Golgi apparatus, effects indicative of increased secretory function, in the pinealocytes from irradiated rats in comparison with those from sham-irradiated controls. Koldaev (*@MR0025*), in 1974, reported that administration of nikethamide immediately following microwave irradiation enhanced the survival of mice and suggested that one effect of such irradiation is depletion of the supply of neuroendocrines.

(b) Effects on Gonadotropins and Growth Hormone

The response of the neuroendocrine system of rats to microwave irradiation was described by Mikolajczyk (*@MR1890*) in 1974. The rats were irradiated under far-field conditions in an anechoic chamber with 2.87-MHz radiation at an average power density of 10 mW/cm^2. The corticosterone levels in the adrenal glands were not changed by 15 or 30 minutes of CW irradiation. Exposure to CW and PW radiation at 5 and 10 mW/cm^2 for 2 h/d for 35 days did not alter the amounts of the gonadotropin-luteinizing hormone or follicle-stimulating hormone. Growth hormone level also was unchanged. One notable observation was that hypophysectomized rats survived two to three times longer than did normal rats when irradiated at 120 mW/cm^2.

Uptake of zinc into the dorsolateral prostate gland is known to be under the control of testosterone and is therefore an excellent measure of the function of the pituitary-testis-prostate endocrine chain. Gunn et al (*@MR0210*), in 1961, showed that acute microwave irradiation of rats diminished the output of androgen. Young male rats were anesthetized and placed in an environmentally controlled chamber, and the scrotum of each was irradiated with 24-GHz microwaves (far-field conditions, power density 250 mW/cm^2). Five minutes of microwave irradiation decreased ^{65}Zn uptake to 55% of control values 13 days after exposure. By 29 days, uptake had returned to normal, and no change in the weight of the dorsolateral prostate was observed. With 10 and 15 minutes of irradiation, uptake decreased to 45 and 30% of control values, respectively, and prostate weight was reduced to 80% of control values. The effects on zinc uptake of administration of two hormones were determined. One international unit (IU) of gonadotropin or 200 µg of testosterone was injected daily for 6 days postirradiation and prior to measurement of prostate weight and zinc uptake. Both values were normal for the 5-minute irradiation after treatment with either hormone but were depressed after the 10-minute irradiation and treatment with gonadotropin.

These results indicated to Gunn et al (*@MR0210*) that microwave irradiation initially affected luteinizing hormone output by the pituitary. Longer exposures prevented a response to the trophic hormone by the interstitial tissue of the testis. Whether that failure was due to tissue damage could not be established by microscopic examination of the testes. Gunn et al compared their observations with effects reportedly produced by exposure to heat and to IR radiation. The fact that higher temperatures in the testes were necessary with these two agents to produce comparable changes in prostate weight and zinc uptake suggested that microwave irradiation produced some athermal effects.

Support for the notion of a general stress reaction in response to exposure to microwave radiation was presented by Houk and Michaelson (*@MR0836*) in 1974. Four hundred young male rats were irradiated with CW 2.45-GHz microwaves in an environmentally controlled anechoic chamber. A 3-hour equilibration period preceded every 2.5-hour irradiation session. When the blood was analyzed for growth hormone, glucose, triglycerides, and cholesterol, the only statistically significant result was a decrease in the concentration of growth hormone in the serum, in comparison with that in sham-irradiated controls, caused by 60 minutes of irradiation at 36 mW/cm^2. The pulsatile nature of growth hormone release was also abolished. This effect occurred in association with a peak in the radiation-induced rises in body temperature of 40.9 C. The results suggested a differential effect of microwave irradiation on the hypothalamic-pituitary axis as well as the extreme sensitivity of the endocrine axes to any type of stress.

(c) Hypothalamic-Hypophyseal-Thyroid Response

A stimulation of thyroid function, indicated by increased iodine uptake, was reported by Fofanov (*@MR0692*), in 1966, for 15 men who had been occupationally exposed to SHF radiation at reported levels of 34-58, 170-218, and

500-760 μW/cm^2 for 5-14 years. A 1972 study by Baranski et al (*@MR0852*) of thyroid function following microwave irradiation implied that the increased uptake of iodine and secretory function observed were due to stimulation of cellular activity rather than to hyperplasia. Twenty adult rabbits were irradiated for 3 h/d with 3-GHz microwaves at an average power density of 5 mW/cm^2 for 4 months. Incorporation of radioactive iodine into the thyroid gland and the concentration of serum protein-bound iodine increased by 50 and 117%, respectively, suggesting increased secretory function. Autoradiographs supported these conclusions. An increased number of cytosomes and an enlarged Golgi apparatus and endoplasmic reticulum were evident in electron micrographs.

Results of a preliminary experiment with rats were reported by Vetter (*@MR2982*) in 1975. Pregnant rats were irradiated for 10 or 20 min/d with 2.45-GHz microwaves at power densities of 5 or 25 mW/cm^2. An anechoic chamber was used, and the animals were exposed on the 6th through 21st days of pregnancy. A radioimmune assay indicated that the thyro-binding capacity of the blood increased with dose, ie, the concentration of thyroid hormone decreased. Measurements of serum iron and iron-binding capacity indicated that the concentration of protein transferrin, and by implication protein synthesis, increased. Vetter interpreted the changes as indicative of adaptation to thermal stress.

A 1972 study by Milroy and Michaelson (*@MR0264*) failed to demonstrate any direct effect of microwave radiation at 2.45 GHz on the thyroid-hypophyseal axis of the rat. Data were obtained for six groups of animals: (1) sets of 4 adult males that were irradiated at 100 mW/cm^2 for 10, 20, 30, or 40 minutes (last dose was lethal), (2) 10 animals subjected at 10 mW/cm^2, 8 h/d for 8 weeks, to simulate occupational exposure conditions, (3) another 10 animals irradiated continuously at 1 mW/cm^2, (4) a comparison group of 10 rats exposed to IR radiation for 10, 20, 30, and 40 minutes at a power density sufficient to raise body temperature to levels comparable with those achieved with similar exposures to 2.45-GHz microwaves at 100 mW/cm^2, (5) a sham-irradiated group, and (6) a nonhandled group.

Thyroid activity was measured at 4 and 8 weeks of irradiation and at 4 and 8 weeks afterward (*@MR0264*). Milroy and Michaelson detected no significant differences in secretion into the blood of tetraiodothyronine (T_4) or uptake of triiodothyronine (T_3) between the microwave- and the sham-irradiated groups. Furthermore, uptake of radioactive iodine was similar in all three irradiated groups at 3 and 6 months postirradiation. Finally, no differences in the levels of thyroid-stimulating hormone (TSH) were noted. Consequently, not only was thyroid function assumed to be normal under the conditions of irradiation employed in these experiments but also hypothalamic activity. Since microwave irradiation at relatively low power density levels produced only slight elevations in the body temperature of the rat and no observable alterations in endocrine activity or thyroid histology, Milroy and Michaelson insisted that these levels are not hazardous to man. This interpretation is supported by the fact that rodents are known to have less efficient thermo-regulatory systems than those of man and dogs and to have their vital organs situated closer to the body surface.

Magin et al (*@MR0115,@MR1710*), in 1974 and 1977, described increased thyroid secretion in dogs locally irradiated with microwaves. The thyroid glands of the dogs were surgically exposed and cannulated, and a microwave applicator was placed in direct contact with the left lobe of each gland. Irradiation at 2.45 GHz was for 2 hours. The incident power density was continually adjusted to maintain a temperature of 44-46 C, 40-42 C, or 38-39 C in the gland. The power densities for these ranges were 236±55, 162±54, and 72±29 mW/cm^2 at calculated SAR's of 190±45, 131±44, and 58±24 W/kg, respectively. The rectal temperatures of the dogs and the temperatures of the control glands remained at preexposure levels during irradiation. The rate of secretion of T_4 by the irradiated gland increased to a maximum within 10 minutes after irradiation was begun and then either leveled off (at the lowest temperature) or declined. The kinetics of release of T_3 resembled that of T_4 in all cases.

Both irradiated and control glands were removed immediately following irradiation and prepared for light microscopic examination (*@MR0115, @MR1710*). Neither degeneration nor other structural changes were evident in the irradiated glands. The fact that localized irradiation caused the transient stimulation of thyroid hormone secretion observed in these experiments ruled out any dependence of this effect on a primary interaction of microwaves with the hypothalamus or the pituitary gland. Magin et al suggested that low levels of heating probably caused an increase in the gland's metabolism, leading to continual enhanced hormone secretion, but that heating to higher temperatures quickly depleted the endogenous hormone supply and damaged the biochemical processes of secretion.

In two 1974 reports concerning the effects of RF and microwave radiation on rats, Demokidova (*@MR2654,@MR2664*) noted a positive correlation between changes in the size of several endocrine glands and various metabolic and growth indices. Irradiation of 199 rats with UHF microwaves (69.7 MHz) at field strengths of 5, 12, and 48 V/m, for 1 h/d for 1.5 months, led to an increase in body weight, decreases in the thickness of the tibial cartilage and in alkaline phosphatase activity, and increases in the weights of the adrenal and pituitary glands. An increase in body weight and decreases in the weights of the thyroid and the adrenals resulted from exposure to HF radiation (14.88 MHz) at 70 V/m for 1, 2, and 4 months. Demokidova (*@MR2654*) concluded that the long-term irradiation had caused inhibition of thyroid gland function.

Single exposures (*@MR2664*), on the other hand, led to decreases in the weights of the pituitary and adrenal glands and an increase in the weight of the thyroid. Rats (308) were irradiated with 3-GHz microwaves either continuously at 153 $\mu W/cm^2$ for 1 hour, or they were irradiated for three variable intervals within a total 2-hour span at 60, 160, 240, or 320 $\mu W/cm^2$. Measurements made at 0.5, 1, 2, and 4 months postirradiation indicated variable changes in the excretion of water, in the concentrations of electrolytes in the urine, and in the alterations of the weights of the glands. Within 5 months after continuous irradiation, all these had returned to control levels. In contrast, significant changes were observed in the concentration of potassium in the urine and the weight of the pituitary gland at 5 months after the intermittent irradiation: Both increased in female rats, whereas both decreased in male rats. The results suggested a relationship between the microwave-induced alterations in endocrine function and various metabolic indices but did not establish any definite cause-effect relationship (see also Demokidova (*@MR1260*)).

The influence of microwave irradiation on the function of thyroid, adrenocortical, and adrenomedullary cells of rats was noted by Parker (*@MR0038*) in 1973. Adult male rats were exposed in an anechoic chamber to CW 2.45-GHz microwaves. Exposure at 10, 15, 20, and 25 mW/cm^2 for 16 hours led to increases in rectal temperature of only 0.4, 0.5, 1.0, and 1.7 C, respectively. Only the last value was significantly different from zero. A power density of 10 mW/cm^2 induced in the adrenal gland a significant increase in phenylethanolamine-N-methyl-transferase activity of 26% and a decrease in epinephrine concentration of 35% but no significant differences in adrenal or plasma corticosterone concentrations or in adrenal pair weight. Four-hour exposures led to no significant changes in any of these values. Six rats were used for each determination. Sixteen-hour exposures at 10, 20, and 25 mW/cm^2 produced insignificant decreases in serum protein-bound iodine and serum thyroxine levels and did not significantly affect the ability of the thyroid to concentrate iodine, measured by the ratio between the concentrations of ^{131}I in the gland and in the serum. On the other hand, a 60-hour exposure at 15 mW/cm^2 decreased those three indices by 28, 53, and 67%, respectively. The last exposure condition increased rectal temperature by only 0.5 C.

In discussing his data, Parker (*@MR0038*) emphasized that 16-hour exposures at low power densities, insufficient to cause surface burns or gross internal thermal damage, produced changes that indicated a response mediated by the sympathetic nervous system at the level of the hypothalamus or below. A pituitary-adrenal response was not evident, except for increased epinephrine release and synthesis. The significant effect of longer exposure on thyroid function at a decreased power density, especially when viewed with regard to the independence of the temperature increase from the duration of exposure, was not explained. Selective heating due to an unequally distributed thermal component was suggested as one possible explanation.

(d) Hypothalamic-Hypophyseal-Adrenal Response

A comparative study of the function of the adrenal cortex in radio operators and in workers living under similar, but nonexposure, conditions was reported by Afanas'yev (*@MR0417*) in 1968. Urine was obtained from 38 specialists who had worked for 24-1,800 hours with SHF radiation apparatus. The concentrations of 17-ketosteroids, 17-oxycorticosteroids, sodium, and potassium were determined, and the ratio between the concentrations of sodium and potassium was calculated. These indices, which reflect, respectively, androgenic, glucocorticoid, and mineralocorticoid activities, were not found to have values significantly different from those determined for a control group of 22 workers. Szady et al (*@MR0383*), in 1976, also found no differences between the urinary excretions of 17-hydroxycorticoids and of 17-ketosteroids by 12 workers who had been exposed to pulse-modulated microwave radiation and 15 unexposed controls.

Dumkin and Korenevskaya (*@MR2629*), in 1973, measured glucocorticoid concentrations in the urine of workers exposed during a prolonged period to SHF radiation. Clinical observations of 20 patients, aged 33-46 and with 10-20 years of service, revealed a complex of vegetative and vascular dysfunctions, cerebral and coronary vascular insufficiencies, pronounced emotional instability, and general weakness. Hydrocortisone, cortisone, and their tetrahydro derivatives and tetra-17-hydroxy-11-deoxycorticosterone were isolated from extracts of urine obtained from these patients, and their concentrations were compared with those measured in urine from 10 healthy individuals. Significant decreases in the excretion of tetrahydrocortisone (26.5%) and cortisone (48%) were found, as well as an increase (140%) in the ratio between the concentrations of hydrocortisone and cortisone.

Administration of epinephrine, which has no effect on glucocorticoid levels in healthy individuals but alters their excretion in patients with hypothalamic lesions, led to increases in hydrocortisone and total glucocorticoid hormone excretion by 50 and 8%, respectively, in patients clinically diagnosed as suffering from "microwave sickness." Since neurotropic poisons capable of producing toxic diencephalopathies also lead to similar elevations, Dumkin and Korenevskaya suggested that the observed changes in glucocorticoid function of the adrenal glands resulted from microwave-induced lesions in the deep structures of the brain responsible for regulation of the pituitary-adrenal cortex axis.

Grigor'eva et al (*@MR2320*) found that 460-MHz radiation at 110 mW/cm^2 was effective in stimulating the secretory function of the pituitary-adrenocortical system in rabbits (total of 70 animals, irradiated for 6 min/d for 12 days): The levels of the catecholamines epinephrine and norepinephrine were increased in the adrenal glands and hypothalamus, and the concentrations of norepinephrine in the blood and heart were greater than normal. Similar results were also reported by Maksimova (*@MR2437*), in 1973, for radiation at the same frequency and power densities. Both reports noted an inhibition of secretion following irradiation at power densities above 300 mW/cm^2.

Effects on the urinary excretion of 17-oxycorticosteroids and the catecholamines adrenaline and noradrenaline were reported by Kardashev and Gersamiia (*@MR2383*) in 1968. Increases in excretion by guinea pigs and rats were observed following 15 minutes of irradiation daily for 10 and 6 days at 18 and 7 mW/cm^2, respectively. Microscopic examination of the tissues also indicated decreased secretory function in the hypothalamus but increased activity in the adrenal glands. The effects lasted for approximately 10 days after irradiation ended. Serdiuk (*@MR2518*), in 1969, and Zalyubovskaya (*@MR0749*), in 1977, reported differential effects of long-term exposures at low power densities on excretion of corticosteroids and catecholamines. These data are included in Table III-6.

Lotz (*@MR0113*) and Lotz and Michaelson (*@MR1704*), in 1976 and 1978, respectively, discussed the physiologic mechanism of the immediate adrenocortical response in rats to acute microwave irradiation. Male rats were irradiated with CW 2.45-GHz microwaves in the far field for 30, 60, and 120 minutes at 13-60 mW/cm^2. The average SAR was 0.16 W/kg per 1 mW/cm^2 of incident radiation. A positive correlation between mean colonic temperature and the mean concentration of corticosterone in the plasma was evident in irradiated rats. Representative values, after irradiation at 30 mW/cm^2 for 30, 60, and 120 minutes, were temperature increases of 0.9, 0.9, and 1.4 C and increases in corticosterone levels of 4.0, 7.4, and 12.5 µg/100 ml, respectively. The results indicated that a power density threshold existed for a given exposure duration, which shifted to lower densities for longer exposures. Stimulation of the adrenal axis was dependent on adrenocorticotropin (ACTH) secretion by the pituitary, since hypophysectomized rats or rats pretreated with dexamethasone showed below-normal levels of corticosterone after microwave irradiation. Lotz interpreted his data as showing that microwave irradiation produces a general hyperthermia that results in adrenal secretion, rather than a primary stimulation of the adrenal glands.

Guillet and Michaelson (*@MR2000*), in 1977, reported that microwave irradiation of neonatal rats led to an increase in adrenal gland weight without a concomitant increase in plasma corticosterone level or responsiveness to ACTH. Eighteen rats were irradiated with CW 2.45-GHz radiation, at 40 mW/cm^2 under far-field conditions, for 5 minutes on each of the first 6 days after birth. An equal number of control rats were sham irradiated. Six rats in each group were killed immediately; body weight, adrenal wet weight, and corticosterone level were measured. Another six were injected intraperitoneally (ip) with 10 milliunits/100 g ACTH, and the last six were reirradiated for 5 minutes. Animals from the second and third groups were killed 20 minutes later, and measurements similar to those described above were made. At the end of the 6-day period of irradiation, colonic temperatures were 1.5-2.5 C above control levels. Plasma corticosterone levels were not significantly different for sham- and microwave-irradiated rats killed immediately after irradiation on the 6th day. Compared with sham-irradiated rats, those irradiated with microwaves responded to ACTH with greater increases in corticosterone levels; however, the increases were similar for those injected with ACTH and those irradiated for a seventh time with 2.45-GHz microwaves. The adrenal weight and adrenal weight:body weight ratio of the rats irradiated for 6 days postnatally were also 23 and 32% greater, respectively, than control values. These results were suggestive of an enhanced developmental process.

A comprehensive report by Michaelson et al (*@MR1718*), in 1977, emphasized that the observed stimulation in the secretion of corticosterone by the adrenal gland following irradiation with 2.45-GHz microwaves was representative of a nonspecific reaction of the hypothalamic-hypophyseal-adrenal (HHA) axis to stress. Michaelson et al based their interpretation on studies they performed with rats and dogs irradiated for 1 hour at thermogenic power densities between 20 and 100 mW/cm^2, and they stated that 20-30 mW/cm^2 was the transitional range in which the effects were noted. Novitski'i et al (*@MR0307*) relied on the same approach in studies performed on 891 rats irradiated with 2.38-GHz microwaves. They determined, however, that 30 minutes of irradiation at 0.01 mW/cm^2 was the threshold for stimulation, signalled by increased secretion of corticotropin-releasing factor by the hypothalamus and of ACTH by the pituitary, a higher concentration of 11-oxycorticosteroids in the plasma, and an altered $Na^+:K^+$ ratio in the blood. These increased with increasing power density from 0.01 to 1 mW/cm^2 but thereafter remained constant up to a power density of 75 mW/cm^2. When rats were irradiated with 2.38-GHz microwaves at 1 mW/cm^2 for 30 min/d, measurements at 10, 20, and 30 days indicated a progressive decline in the four indices from a maximum at 10 days to below control values at 30 days. Novitski'i and colleagues set the threshold for harm by microwave radiation at power densities in the range of 1-10 mW/cm^2.

In a 1977 experiment designed to take into account the elevation of body temperature, and therefore of serum corticosteroid concentrations, induced by handling and the circadian rhythmicity of adrenocorticoid function, Lu et al (*@MR1989*) analyzed the immediate endocrinologic effects of microwave irradiation on rats. Eighty-six young male rats were acclimatized to the routine handling and measurement procedures used in an irradiation situation for 2.5 weeks prior to the actual exposure. Furthermore, a 3-hour period was allowed for equilibration to the cage and rectal probe before irradiation with CW 2.45-GHz radiation. Sham-irradiated controls were compared with rats exposed for 1, 2, 4, or 8 hours at 1, 5, 10, or 20 mW/cm^2 for differences in rectal temperatures, for concentrations of corticosteroid, thyroxine, and growth hormone and for thyroid and adrenal weights.

During the acclimatization period, Lu et al (*@MR1989*) detected wide variability in rectal temperatures, which was attributed partly to the influence of circadian rhythm and partly to handling. They also observed a linear relationship between corticosterone level and rectal temperature. Only after 4 or 8 hours of irradiation at the highest power density of 20 mW/cm^2 did rats exhibit statistically reliable elevations of temperature above control levels; at 10 mW/cm^2 or below, irradiation advanced by several hours the appearance of higher rectal temperature within the circadian period. Eight hours of irradiation at 20 mW/cm^2 also produced a significant depression of the concentration of corticosterone to 69.6% of that in sham-irradiated control rats and depressed the concentration of thyroxine to 68.4% of that in controls. No significant alterations in the concentrations of these two hormones were observed at other power densities or durations or at any exposure condition for serum growth hormone. A similar lack of effect was evident for body, adrenal, and thyroid weights. Lu and colleagues concluded that thermogenesis leading to increased body temperature was the primary stimulus for the effects observed.

Effects on the Central Nervous System

Reports of radiation-induced changes in the CNS are listed in Table III-7. Several of the tabulated reports are mentioned in General Physiologic and Other Effects. Alterations in the EEG and electrocorticogram (ECoG) are also discussed in this section, as is the auditory response to microwave radiation.

(a) Ultrastructure of the Central Nervous System

The results of experiments with dogs were reported in 1959 by Searle et al (*@MR0932*). The head of each dog was irradiated with 2.45-GHz microwaves at 500 and 800 mW/cm^2 for periods ranging between 1 and 7 hours. Irradiation led to similar increases of temperature in the frontal lobe of the brain, the

TABLE III-7

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse (250)	2.854	16.5	15 min	Cortical hemorrhages	Minecki and Bilski (*@MR1110*)
"	"	30.5	5 min	"	"
"	"	64	1.5 min	"	"
Mouse and rat	2.4	10	"Chronic"	Increased number of oligodendrocytes and astrocytes, hyperemia of capillaries	Aleksandrovskaya (*@MR0420*)
Rat (15)	2.45	2.3 mW/g	5 h/d for 110 d	Increased incidence of myelinated figures in dendritic processes	Switzer and Mitchell (*@MR1776*)
Rat	1.12	0.2 (PW), 2.4 (CW)	30 min	Increased permeability of blood-brain barrier	Frey et al (*@MR0710,@MR3009*)
"	1.3	0.03-3 (temperature controlled)	20 min	Increased permeability of blood-brain barrier; dependent on frequency, peak power, and pulse characteristics	Oscar and Hawkins (*@MR1736*)
Chinese hamster	2.45 (CW)	10	2, 8 h	Light and electron microscopic observations of increased permeability of blood-brain barrier, effect not localized to any specific brain areas	Albert (*@MR2948*)
Rat and Chinese hamster	2.45	10	2 h	Temporary increase in microwave-induced permeability of blood-brain barrier (2 h)	Albert (*@MR2936*)
Rabbit (92)	2.307	30, 50, 75 W (irradiation localized to head and abdomen)	10, 20 min	Increased permeability of blood-brain barrier to phosphate	Polyashchuk (*@MR0135*)

TABLE III-7 (CONTINUED)

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	1.6	80 (long axis of rat parallel to E-field)	10 min	Increase in brain tissue content of iron, copper, and magnesium; decrease in zinc content of hypothalamus; effects mimicked by hot air treatment sufficient to raise rectal temperature 4 C	Chamness et al (*@MR3000*)
"	1.6 (CW)	20-80 (anechoic chamber; long axis of animal parallel to E- or H-field)	10-130 min	E-field polarization produced larger increases in brain and rectal temperatures than did H-field polarization and led to energy density-dependent decreases in dopamine and norepinephrine content in hypothalamus; serotonin content was unchanged.	Merritt et al (*@MR3016*)
"	1.6	80	10 min	Decreased levels of 5-HT, homovanillic acid, norepinephrine, and dopamine (mimicked by convection heating)	Merritt et al (*@MR1085*)
"	2.45	10	8 h/d for 8 d	Increase in neurotransmitters and sensitivity to PGE	Catravas et al(*@MR0335*)
"	2.8 (PW)	10	8 h/d for 3-5 d	No changes in GABA and L-glutamate decarboxylase levels in brain	Zeman et al (*@MR1010*)
"	"	10	4 h/d for 4-8 wk	"	"
"	"	40	20 min	"	"
"	"	80	5 min	"	"
"	3	40	1 h	Increase in turnover of 5-HT; norepinephrine unchanged	Snyder (*@MR0296,@MR1391*)

TABLE III-7 (CONTINUED)

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	3	10	8 h/d for 7 d	Decrease in turnover of 5-HT; heated animals showed no effects	Snyder (*@MR0296,@MR1391*)
"	3, 10	1-10	--	Morphologic changes in peripheral nervous system, histochemical changes in CNS	Gordon et al (*@MR0799*)
"	3	14	2 h	Survival time increased by pretreatment with the narcotics chloral hydrate and sodium barbital and with the analeptic bemegride, but decreased by use of adrenergic and cholinergic agents and serotonin	Lobanova (*@MR1587*)
"	3	7-13.3, 19-31, and 40-110	30-min sessions, 14-40 times; 30 min; 5-15 min/d for 75 d, respectively	Degenerative changes in nervous system after exposures (single and multiple)	Tolgskaya et al (*@MR2548*)
"	37.5-60	1	15 min/d for 60 d	Demyelination of peripheral nerve fibers	Zalyubovskaya (*@MR0749*)
Chinese hamster (60)	2.45	25 (far field)	22 d	Vacuolization and degeneration in hypothalamic cells and axons	Albert and DeSantis (*@MR0164*)
"	"	50 (far field)	0.5-24 h	No changes in cerebral, cerebellar, and spinal cord cells up to 1-2 wk post-irradiation	"
Rabbit (30)	3 (CW and PW); 10 (PW)	5	3 h/d for 60 d	Histopathologic changes, reversible (1 d) changes in EEG, no changes with PW 10-GHz irradiation	Baranski and Edelwejn (*@MR0006,@MR0851*)
Rabbit (40)	10 (CW and PW)	5 and 10	15 min	"	"

TABLE III-7 (CONTINUED)

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit (40)	3 (CW and PW)	5-30	15 min at 5-mW increments	Histopathologic changes, reversible (1 d) changes in EEG, no changes with PW 10-GHz irradiation	Baranski and Edelwejn (*@MR0006,@MR0851*)
Chicken	0.147 and 0.450	0.1-1 (modulated) at 6-20 Hz)	--	Increase in Ca^{+2} efflux from cerebral tissue (in vitro experiments)	Bawin et al (*@MR2848, @MR2856,@MR2861,@MR2871*), Blackman et al (*@MR3132*)
Cat	0.918	20 and 30 mW/cm^3 (localized to thalamic region)	--	Increased latency in thalamic evoked response, changes mimicked by heating	Taylor et al (*@MR0151*)
"	2.45, 10 (PW)	200 (near field, to exposed nerve bundles in decerebrate cats)	--	Thermal stimulation of peripheral nervous system (to 45±2 C) by microwave and IR radiation or treatment with hot air, warm water, and high-resistance electric wire produced behavioral changes and neurologic effects characterized by rise in blood pressure, pupillary dilation, changes in heart rate and respiration, and crossed extension reflex.	McAfee (*@MR2125,@MR2887*)
Cat (4)	"SHF"	5-30	2 h/d for 5 d	Degeneration at receptors and spinal ganglia of neurons innervating heart muscle; muscle tissue unchanged	Pervushin (*@MR1902*)
Cat	2.46-10	--	--	Nociceptive response (peripheral nerve stimulation)	McAfee (*@MR1973*)
"	10-30	--	--	Nociceptive stimulation	Nieset et al (*@MR1634*)
"	10 (PW)	200	--	Injury reflex followed direct irradiation of sciatic, radial, and trigeminal nerves	McAfee (*@MR0243*)

TABLE III-7 (CONTINUED)

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	"VHF"	5	1 wk, 1 mo, and 5 mo	Changes in ECoG appeared after 48-h irradiation; disappeared 48-72 h after irradiation was halted	Bertharion et al (*@MR0781*)
Rat (8)	3 (PW)	5 (far field)	10 d	Synchronization of ECoG for 1-2 min	Servantie et al (*@MR0291*)
Guinea pig (2)	2.45	30 W/kg (multimode cavity irradiation; 60-Hz modulation, halfwave sinusoidal)	Irradiation continued until rectal temperature reached 42 C	Minimum in latency of visually evoked electrocortical responses occurred at 39.5 C during body cooling	Justesen and Bruce-Wolfe (*@MR2610*)
Rabbit (60)	(1) 0.05 (CW) (2) 2.5 (CW)	(1) 600 pW/cm^2 to 10 (u)W/cm^2 (2) 0.5-10 (u)W/cm^2	(1) 10-12 h/d for 120 d (2) 8 h/d for 120 d	Power densities between 1.9 and 10 (u)W/cm^2 (case 1) and between 5 and 10 (u)W/cm^2 (case 2) synchronized cortical rhythms	Dumanskii and Shandala (*@MR1832*)
Rabbit (24)	--	0.1	30 min	Deactivation predominated in hypothalamus and cortex but not in brain stem	Bychkov and Dronov (*@MR2634*)
Rabbit (172)	0.3, 0.576, and 2.5	0.02-50	5 min	Rhythm slowed and amplitude decreased; latency of these changes was a linear function of power density.	Gvozdikova et al (*@MR1551*)
Rabbit (34)	0.46	2 and 5	10 min	Frequency of nerve cell spiking and assimilation of light flash rhythm (13-25 Hz) increased at 2 mW/cm^2; assimilation and frequency of discharge decreased, whereas synchronization of electric activity increased at 5 mW/cm^2; hippocampus and hypothalamus more sensitive than thalamus to RF	Faitel'berg-Blank and Perevalov (*@MR3044*)

TABLE III-7 (CONTINUED)

CENTRAL NERVOUS SYSTEM EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit	3 (CW and PW); 10 (PW)	5	3 h/d for 60 d	No changes in EEG after 10-GHz irradiation, PW 3-GHz irradiation desynchronized EEG and slowed spikes from occipital EEG, no microscopic changes	Baranski and Edelwejn (*@MR0851*)
Rabbit	3 and 10 (CW and PW)	5-30	15 min at 5-mW increments	"	"
Rabbit (24)	3	0.06-0.32	1 h/d for 2 mo	Transient synchronization and desynchronization of EEG; nonlinear potential amplification	Bychkov et al (*@MR2668*)
Cat (12)	0.147	1 and below	--	Operant conditioning by amplitude-modulated radiation, production of specific rhythms and reinforcement of spontaneous rhythms in EEG	Bawin et al (*@MR0768*)
Cat	0.918, 2.45	1.3-52 output; incident power density 0.6 mW/cm^3 at brain surface, 1.88 mW/cm^3 at thalamus	Constant 1 mWh/cm^2	Changes in conduction and transmission latencies and amplitude of evoked potential, mimicked by conduction heating	Guy et al (*@MR0089*)
"	1.2, 1.535 (PW)	0.03 (average)	--	Brain-stem evoked potentials	Frey (*@MR1839*)
"	2.45	1-20	--	Spinal cord synaptic transmission unchanged	McRee et al (*@MR1952*)
Dog (24)	2.45	88 and 176	20 min-1 h for 3 d	EEG synchronization	Lambert et al (*@MR1180*)

*Unless otherwise specified

cisterna magna, the midbrain, and the rectum; however, blood pressure, heart rate, cerebrospinal fluid (CSF) pressure, respiratory rate, and transaminase activity in the CSF did not change. The lack of an effect on transaminase activity in the CSF concomitant with an increase in serum transaminase activity at 12-48 hours suggested that neither the brain cells nor the blood-brain barrier was damaged. As described in a 1961 report, Minecki and Bilski (*@MR1110*) subjected 250 male and female mice to microwave radiation and examined various organs, including the brain, for histopathologic changes. Each group of animals was exposed six times in 6 days. Few structural changes were evident in the sections of the brains examined, except for some hemorrhaging into the cortex.

Baranski and Edelwejn (*@MR0851,@MR0006*), in 1967 and 1975, reported the results of two series of experiments designed to explore the effects of multiple and single exposures to microwave radiation on the CNS of male rabbits. In the first series of experiments, the power density was 5 mW/cm^2, and 30 animals were exposed 3 h/d for 60 days to PW 3-GHz, CW 3-GHz, and PW 10-GHz microwave radiation. Forty rabbits were irradiated in the second series with PW and CW 10-GHz radiation at 5 and 10 mW/cm^2. The second group of animals was irradiated at 3 GHz and power densities of 5-30 mW/cm^2. The 40 rabbits were given 15-minute exposures for each 5-mW/cm^2 increment until the full range of power densities had been employed. Temperatures of the rectum, the cerebral cortex, and the subcutaneous tissue of the head were recorded both before and during irradiation.

Results of long-term exposure to PW radiation at a frequency of 10 GHz revealed no microscopically detectable changes in brain structure (*@MR0851*). Structural changes following long-term exposure to PW 3-GHz radiation included deficient Nissl body (or tigroid) content of cells of many CNS areas, vacuolization, hyperchromatic staining, some features observed in Nissl's degeneration, and metachromatically stained spherical bodies in the white matter of the brain. Animals exposed once at 10 GHz and 5 and 10 mW/cm^2 exhibited no morphologic changes within the brain and its membranes. Pulsed radiation at 3 GHz and 15 mW/cm^2 produced slight congestion of the meninges and superficial cerebral cortical vessels. With increasing power densities, more marked congestion was observed. At 30 mW/cm^2, red cell effusions and perivascular transudates were noted. Temperature changes were negligible except for a 4.5 C increase in brain temperature at 3 GHz and 30 mW/cm^2.

In a 1972 report, Baranski (*@MR1808*) stated that, in contrast to the production of definite thermal lesions in rabbits following a 3-hour exposure to 3-GHz microwaves at 25 mW/cm^2, exposure at 3.5 mW/cm^2 produced no observable effects. When 3-hour daily exposures at 3.5 and 5 mW/cm^2 were repeated for 3 months, morphologic changes, characterized by the presence of spherical metachromatic bodies in the myelin sheaths and glial cells in the white matter of the brain and cerebellum, and decreases in acetylcholinesterase and succinic acid dehydrogenase activities were noted. Furthermore, under long-term irradiation conditions, PW irradiation was found to evoke more pronounced changes than CW irradiation.

In a 1968 article, Aleksandrovskaya et al (*@MR0420*) presented qualitative results from a series of experiments designed to examine the effects of microwave radiation on brain functions and on the neuroglial elements of the CNS. Rats and mice were irradiated for 30 minutes at 2.4 GHz and 10 mW/cm^2. Microscopic examination of sections of brains from exposed rats and mice revealed significant increases in the concentrations of oligodendrocytes and astrocytes as well as hyperemia of the capillaries. Tolgskaya et al (*@MR2548*), in 1959, described degeneration of the nervous system of rats following exposure to 3-GHz microwaves at 19 mW/cm^2 and above.

Albert and DeSantis (*@MR0164*), in 1975, reported the results of examinations of the CNS of 60 adult male and female Chinese hamsters irradiated (far field) in an anechoic chamber with CW 2.45-GHz microwaves at 25 mW/cm^2 for 14 h/d for 22 days and at 50 mW/cm^2 for 30 minutes to 24 hours. Vacuolization, loss of basophilia, chromatolysis, and some frothing were observed at the light microscope level in the neuronal cytoplasm of hypothalamic nuclear groups, but not in the cerebral, cerebellar, mesencephalic nuclear trigeminal, or ventral horn cells of the spinal cord. In addition, slight degeneration of axons in the hypothalamus became evident when special neurocytologic stains were used.

No evidence of gliosis, hemorrhage, or perivascular edema was observed. Electron microscopic findings essentially confirmed light microscopic results, with the exception of a higher incidence of myelin figures in the dendrites of experimental animals than in those of controls. The detectable changes were less extensive 6-10 days after exposure than they were immediately following exposure.

Another 1975 report by Albert and DeSantis (*@MR2937*) contained several electron micrographs of brain tissue obtained from 60 Chinese hamsters irradiated at 10 or 25 mW/cm^2 with 1.7-GHz radiation. An anechoic chamber was used for microwave and sham irradiation, which lasted for 30 to 120 minutes. Comparisons of animals killed immediately or 13-15 days postirradiation indicated long-lasting morphologic changes in the hypothalamus and subthalamus; the neurons appeared swollen and contained more vacuolated and less basophilic cytoplasm than the neurons of control animals. The blood vessels appeared normal, however, and no hemorrhaging was evident; other areas of the brain appeared to be unaffected by the irradiation.

In a companion study to a 1977 report by Mitchell et al (*@MR1991*) on microwave-induced behavioral changes, Switzer and Mitchell (*@MR1776*) described the effects of 2.45-GHz radiation on the ultrastructure of the cerebral cortex. Fifteen female rats were irradiated, at an average SAR of 2.3 mW/g, for a total of 110 sessions of 5 hours each, 5 times a week. For irradiation, each rat was restrained in a polystyrene cylinder placed on

Styrofoam blocks within an environmentally controlled multimode cavity chamber (ie, a modified microwave oven). Fourteen rats served as sham-irradiated controls. A comparison of the rectal temperatures of the two groups of animals, in which the Student's t-test was used, revealed no significant differences during the course of the experiment. Electron micrographs of the brain prepared 6 weeks after the end of irradiation showed three times as many ($P<0.05$) myelin figures in the dendritic processes of the cortical tissues of irradiated animals as in those of unirradiated controls. No other structural abnormalities in this area of the brain were noted, and the neurons and synaptic complexes appeared no different from those of controls.

Frey et al (*@MR3009,@MR0710*) described the increased permeability of the blood-brain barrier of rats caused by microwave radiation. Anesthetized, immobilized rats were placed in an anechoic chamber and irradiated for 30 minutes with 1.12-GHz microwaves. A 4% solution of sodium fluorescein was injected intravenously (iv); several minutes later the brain was removed and sectioned and the distribution of dye was determined by ultraviolet (UV) microscopy. Both PW radiation at an average power density of 0.2 mW/cm^2 (0.5-ms pulse width, pulse repetition frequency of 1,000 pps) and CW radiation at 2.4 mW/cm^2 were effective in increasing the amount of dye in the lateral ventricles and diencephalon of the brain. However, PW radiation produced an almost twofold greater dye uptake than did CW radiation. The brains of sham-irradiated controls did not fluoresce.

A light and electron microscopic study of microwave radiation-induced alterations in the blood-brain barrier indicated to Albert (*@MR2948*) that power densities of 10 mW/cm^2, which he considered to be nonthermogenic, were effective in increasing permeability. The 1977 report described nonlocalized increases in the penetration of a 40,000-molecular weight enzyme across the capillary wall following 2 or 8 hours of irradiation with 2.45-GHz microwaves. Further study (*@MR2936*) suggested that the changes were reversible. Permeability in rats and hamsters irradiated with 2.8-GHz microwaves returned to normal within 2 hours after irradiation. Increased permeability of the blood-brain barrier of rabbits to phosphorus was reported by Polyashchuk (*@MR0135*).

In 1977, Oscar and Hawkins (*@MR1736*) described the use of a radioactive tracer technique to study microwave-induced changes in permeability of the blood-brain barrier. Male rats were irradiated for 20 minutes in an anechoic, temperature-controlled chamber with 1.3-GHz microwaves at power densities between 0.03 and 3 mW/cm^2. They were then removed from the chamber and injected (right carotid artery) with one of three radioactive isotope mixtures. These contained ^3H-labeled water and one of three ^{14}C-labeled saccharides (mannitol, inulin, or dextran) of widely differing molecular weights but all normally incapable of penetrating into the brain. The $^{14}C:^3H$ ratios in the hippocampus, cortex, hypothalamus, cerebellum, and medulla were compared with that in the original injection mixture to measure the relative uptake by each of the structures.

The results indicated peak power density-dependent increases in permeability (*@MR1736*). Pulsed microwave radiation at an average power density of 0.3 mW/cm^2 (10-μs pulse width, 50 pps) was more effective than pulsed radiation at 2.0 mW/cm^2 (10-μs pulse width, 1,000 pps) in increasing the uptake of mannitol by the hypothalamus, cerebellum, and medulla of previously anesthetized rats. The respective increases in the medulla were 3.7 and 2.9 times the control values. Less than twofold increases were noted in the hypothalamus and cortex. The radiation-induced (PW, 0.3 mW/cm^2) increases in uptake of inulin were similar to the increases in mannitol uptake and also statistically significant ($P<0.01$ or below) in comparison with controls. Dextran uptake was unchanged. Rats anesthetized 8 minutes or 4 hours after irradiation with pulsed microwaves at 0.3 mW/cm^2 showed similar increases ($P<0.01$ and below) in uptake of mannitol in the three brain regions mentioned above. By 24 hours, uptake had returned to control values.

A final comparison indicated that CW and PW (0.5-μs pulse width, 1,000 pps) microwave radiation at average power densities between 0.3 and 3.0 mW/cm^2 produced similar increases in the uptake of mannitol by the medulla (*@MR1736*). Maximum increases of approximately 2.5 and 2.2 times the control value occurred at near 1.0 mW/cm^2 for CW irradiation and near 0.4 mW/cm^2 for PW irradiation, respectively. With PW radiation of different pulse characteristics (10-μs pulse width, 5 pps), the increase occurred at 0.03-0.05 mW/cm^2. Smaller but significant increases in uptake by the cerebellum and hypothalamus were mentioned, but no data were presented. Oscar and Hawkins concluded that the microwave effect was dependent on frequency, peak power, and pulse characteristics. They did not investigate whether local heating due to hot spots in the neck region caused the increased permeability after irradiation at nonthermogenic power densities.

A 1978 summary (*@MR3137*) of US Air Force research efforts to corroborate the reported changes in blood-brain barrier permeability emphasized that no alterations were observed. That report stated that attempts to replicate several of the above experiments produced either no or statistically insignificant changes at power densities as high as 132 mW/cm^2. The consequences of small, selective changes in permeability (if they do occur) were also questioned. As reported in 1977, Merritt (*@MR1716*) also could not replicate the findings of Oscar and Hawkins.

(b) Concentrations of Neurotransmitters and Other Biochemicals

Snyder (*@MR1391,@MR0296*), in 1970 and 1971, described neurochemical alterations in rats subjected to single and multiple exposures of thermally significant microwave radiation. Groups of 12 adult male rats were used. Each animal was placed with its lateral aspect normal to the direction of propagation of a vertically polarized 3-GHz microwave field. The animals were irradiated for either 1 hour at 40 mW/cm^2 or 8 h/d for 7 days at 10 mW/cm^2 and compared with two control groups, one of which was sham irradiated. Rectal temperatures were monitored. Following the single exposure, the steady-state level of 5-hydroxyindoleacetic acid (5-HIAA) in the forebrain and of 5-hydroxytryptamine (5-HT or serotonin) in the hindbrain increased from 0.27 to 0.38 and from 0.96 to 1.32 μg/g, respectively. These were increases of approximately 39%. Increases in 5-HT turnover and synthesis were not observed after the long-term irradiation. In fact, the brain level of 5-HIAA and the rate constant for removal of 5-HIAA were reduced by microwave irradiation to 0.67 and 0.36, respectively, of the values obtained with sham-irradiated controls. These values corresponded to a calculated turnover rate of 5-HT, which was 0.22 of the control value. Under similar conditions, concentrations of norepinephrine in the brain were unchanged from control values.

An attempt to determine the immediate cause of such disparate results revealed that two distinct mechanisms were operating (*@MR0296*). Under single-exposure conditions, body temperatures were observed to rise an average of 2.9 C. Heat stress was evident, and 4 of the 12 irradiated animals died. Snyder reported that his findings of increased turnover of 5-HT matched previous results obtained with rats maintained solely under ambient temperature conditions sufficiently high to raise mean colonic temperatures by the same amount. Hence, he attributed the increased 5-HT turnover brought about by a single exposure at 40 mW/cm^2 to thermal stress. The multiple-exposure schedule also led to a 1-2 C increase in body temperature, which returned to normal by 18 hours postexposure. Rats maintained at 34 C, 8 h/d for 7 days, also showed a similar increase in temperature; however, no effects on 5-HT levels in the brain were found.

Since thermal factors could be ruled out, Snyder (*@MR0296*) then measured the activities of four enzymes involved in the synthesis of 5-HT and norepinephrine. Tyrosine hydroxylase and monoamine oxidase were unaffected by irradiation; tryptophan hydroxylase and aromatic amino acid decarboxylase were reduced to approximately 75% of control levels. These factors were insufficient to account completely for the observed reduction in turnover of 5-HT. Decreased tryptophan availability, due to altered transport into the brain or lowered circulating tryptophan levels, was suggested but not tested. Snyder's earlier related study (*@MR1391*) had indicated that the effect of microwave irradiation on turnover of serotonin could be due to a nonthermal mechanism. He proposed at that time that a direct microwave-induced reduction in synaptic transmission by serotonergic neurons occurred.

In 1973, Nelson (*@MR1150*) reported irradiating the heads of mice at 2.45 GHz in a 1-kW commercial microwave oven. From three to seven anesthetized animals were exposed for 3 seconds at an unspecified power density, and the results were compared with those of a control group. Only the subcortical glucose-6-phosphate (G-6-P) and cortical lactate increased significantly. Slight increases were noted in the concentrations of glucose in the cortical and subcortical areas and of G-6-P in the cortical areas of the brain. Levels of cortical and subcortical glycogen, adenosine triphosphate (ATP), phosphocreatine, and fructose diphosphate (FDP) were significantly decreased. Concentrations of lactate in the subcortex of irradiated animals were also found to be below control values. The increased concentration of glucose was attributed to the effects of anesthesia, since an elevation was also noted in control animals. Similar changes were obtained when the heads of decapitated mice were irradiated and the brains assayed for the above metabolites.

Zeman et al (*@MR1010*), in 1973, noted the effects of single and multiple microwave irradiation on levels of gamma-aminobutyric acid (GABA) and L-glutamate decarboxylase in the rat brain. Far-field irradiation with PW (500 pps with a 1-µs duration) 2.86-GHz microwave radiation was performed in an anechoic chamber. Groups of eight animals were used, and appropriate controls, ie, sham-irradiated and unstressed rats, were included. The first set of rats was irradiated at 10 mW/cm^2, 8 h/d for 3 or 5 days. The second set was irradiated at 10 mW/cm^2 also, but for 4 h/d, 5 d/wk for 4 or 8 weeks. Short-term exposures of rats were made at 40 mW/cm^2 for 20 minutes or 80 mW/cm^2 for 5 minutes. Gamma-aminobutyric acid and L-glutamate levels were determined by isotopic assay 18 hours postirradiation for multiply exposed animals and immediately after acute irradiation for experimental and control animals. The concentrations of the neurotransmitter GABA in the brains of the irradiated and the control rats were not significantly different.

In 1976, Merritt et al (*@MR1085*) described the effects of microwave radiation on various neurotransmitters and their metabolites. Male rats were irradiated at 1.6 GHz and 80 mW/cm^2 for 10 minutes. The animals were placed in cylindrical holders in an anechoic chamber at a distance of 43 cm from a horn antenna, and rectal temperatures were monitored. Concentrations of 5-HIAA, 5-HT, norepinephrine, and dopamine were measured in the following areas of the brain: hypothalamus, corpus striatum, midbrain, hippocampus, cerebellum, medulla, and cortex. Homovanillic acid was measured only in the corpus striatum, since detection in other areas was not possible. Control animals were heated until their rectal temperatures increased to slightly less than the average attained during microwave irradiation. A second control group of nonheated rats was also used for comparison. In several areas of the brain, neurotransmitter levels in the irradiated rats were below those in the second control group. Merritt et al observed reduced concentrations of neurotransmitters in the same brain areas in heated and irradiated animals and postulated that microwave-induced temperature changes were responsible for the decreases.

Merritt et al (*@MR3016*) reported in 1977 that CW 1.6-GHz radiation was effective in decreasing the concentration of neurotransmitters in the basal hypothalamus of the rat. Irradiation was for 2 hours in an anechoic chamber at 10, 20, and 80 mW/cm^2. Decreases in the concentrations of dopamine and norepinephrine of up to 40% after exposure at 80 mW/cm^2 were found to occur simultaneously with an increase in brain temperature (up to 5 C) when the E-field was polarized parallel to the long axis of the rats. No changes in the concentration of serotonin were found, and H-field polarization produced no effects on the concentrations of neurotransmitters or on brain temperature.

Chamness et al (*@MR3000*), in 1976, reported that short-term (10 minutes) irradiation with 1.6-GHz microwaves at 80 mW/cm^2 produced in several areas of the brain an increase in the concentrations of iron, copper, and magnesium but a decrease in that of zinc. Because similar results were noted in animals subjected to a hot air environment, the effect of irradiation was considered to be wholly thermogenic.

As reported by Baranski and Edelwejn (*@MR0006*) in 1975, a series of experiments was conducted to determine the effects on rabbits of far-field 2.95-GHz irradiation. Acetylcholinesterase activity in various areas of the brain was found to decrease, especially in the reticular formation. Incorporation of ^{32}P into the lipid and nucleic acid fractions of homogenized brain tissue was less in irradiated rabbits than in controls. Reductions were highest in PW irradiated animals. Baranski and Edelwejn found microscopic evidence of decreased Nissl body content and increased affinity for basic stains and postulated that microwave radiation may affect the metabolism of glial cells and, possibly, the integrity of myelin sheaths within the brain.

Catravas et al (*@MR0335*), in 1976, reported on the effects of 2.45-GHz microwave radiation on the concentrations of AMP and neurotransmitters in the brains of male rats. Each animal was exposed at 10 mW/cm^2, 8 h/d for 8 days; controls were sham irradiated. Microwave irradiation caused an increased sensitivity of the brain adenyl cyclase to prostaglandin (PG) E, with the increase more apparent in animals killed 8 hours, rather than immediately, after irradiation. Slight increases in 5-HT and tryptophan hydroxylase activities were observed in the hypothalamic-thalamic region, but no changes in monoamine oxidase levels were detected. A 1974 report by Lobanova (*@MR1587*) indicated that pretreatment with serotonergic and adrenocholinergic agents increased the duration of survival of rats irradiated with 3-GHz microwaves at 14 mW/cm^2.

Bawin et al (*@MR2856*) proposed a mechanistic explanation for the interactions of the central and peripheral nervous systems with weak oscillating electromagnetic fields and asserted that these interactions are responsible for some of the behavioral, electrophysiologic, pharmacodynamic, and biochemical effects observed in animals. Their studies (*@MR2848,@MR2856,@MR2861,@MR2871*) focused on efflux of Ca^{2+} from cerebral tissue following exposure to extremely low or low-frequency amplitude-modulated RF fields. In 1978, Bawin and collaborators (*@MR2856*) reported that cerebral tissue isolated from chicks responded to 147- and 450-MHz radiation with modulation-dependent increases in Ca^{2+} release. Significant increases in efflux were observed with RF fields amplitude modulated at frequencies between 6 and 20 Hz and at power densities between 0.1 and 1 mW/cm^2. Maximum increases of 10-15% occurred at 16 Hz and 1.0 mW/cm^2.

The effect of 450-MHz radiation in isolated chick cerebral hemispheres was described by Bawin et al (*@MR2871*) in 1978. The hemispheres were preincubated in physiologic saline solution containing radioactive Ca^{2+} for

30 minutes, then rinsed, and finally bathed for 20 minutes in fresh testing solution containing no radioactive Ca^{2+}. Irradiation with a 450-MHz radiofrequency field modulated at 16 Hz took place in a horn radiator lined with anechoic material. The "semi-far field" conditions yielded an incident field with a power density of 0.75 mW/cm^2 and E-field strength of 53 V/m, which produced a gradient in the tissue between 5 and 10 V/m. The opposite hemisphere served as a control for each experiment, and the concentration of $^{45}Ca^{2+}$ in the bathing solution was determined by radioassay. Irradiation stimulated efflux by approximately 13% ($P<0.05$). There was no significant difference in efflux compared with controls in Ca^{2+}-free medium, whereas the addition of H^+ further increased efflux to 22% above control values. The omission of HCO_3^- from the medium decreased efflux in controls, but irradiation had no additional effect. The presence of La^{3+} decreased efflux in controls in HCO_3^--free medium, and irradiation caused a further significant decrease ($P<0.01$). Blackman et al (*@MR3132*), in 1977, corroborated the results of Bawin and colleagues.

In 8 of 12 experiments using awake trephined cats, Bawin (*@MR2861*) reported that 450-MHz irradiation stimulated efflux of Ca^{2+} from the cerebral cortex. The modulation conditions were similar to those described above except that power densities of 0.375 and 1.0 mW/cm^2 were used. Efflux was monitored in these experiments for 100 minutes after "loading" with $^{45}Ca^{2+}$. Irradiation took place between 60 and 80 minutes during the monitoring; thus, each animal served as its own control.

What has become evident from these studies of Bawin and colleagues is that Ca^{2+} binding is sensitive to weak E-fields oscillating at low frequencies. The effects are limited to neural tissue, since release of Ca^{2+} by muscle tissue is unaffected by irradiation, and RF fields must be modulated at frequencies in the extremely low frequency range to cause an effect (*@MR2848*). The existence of "windows" or ranges in the power density and in the frequency of amplitude modulation of the field, which can be "tuned" to yield a maximum effect on Ca^{2+} efflux, has been implied. Bawin and coworkers are attempting to correlate such field parameters with electrochemical gradients that exist within the brain and that possibly determine neuronal excitability.

(c) Peripheral Nervous System

A 1957 report by Pervushin (*@MR1902*) described extensive morphologic alterations in the afferent neurons to the heart following SHF irradiation. Four cats were exposed at 5, 10, and 30 mW/cm^2 for 2 h/d for 1-5 days. Microscopic examination after 5 days of irradiation revealed degeneration of the nerve endings on the muscle and of spinal ganglia but no changes in the muscle tissue of the heart. Zalyubovskaya (*@MR0749*) noted in 1977 that short exposures to microwave radiation at 1 mW/cm^2 led to degenerative changes in the cells of the peripheral nervous system.

In 1975, Taylor and Ashleman (*@MR0304*) reported the results of experiments designed to measure the effects of microwave radiation at 2.45 GHz on the dorsally exposed lumbar region of the spinal cord of cats. The exposed area was immersed in a temperature-controlled bath of Ringer's solution, and the temperature of the spinal cord was recorded throughout the study. The nerve to the gastrocnemius muscle was isolated and subjected to specific electric stimulation to elicit a recordable monosynaptic potential in the ventral nerve root. The anesthetized cats were irradiated at incident powers of 7.5 and 3.75 W, sufficient to give absorbed power ratios of 1.6 and 0.8 W/cm^3, respectively. When the temperature of the bath was maintained at 37.5 C, decreases in latency and potential amplitude occurred more slowly at 3.75 W than at 7.5 W. With no temperature control, the above changes occurred more rapidly. Simple heating of the Ringer's solution produced similar variations but at a slower rate. Cooling returned the ventral nerve root potential to its preirradiation characteristics. The similarity in the responses produced by irradiation and conductive heating suggested that the microwave effect on nervous system mechanisms was thermal in nature.

Nieset et al (*@MR1634*) described in a 1960 report the so-called nociceptive effect on the peripheral nervous system of the cat. Local heating sufficient to raise the temperature of tissue supporting the nerve to 45 C was found to evoke a potential without damaging the nerve fiber. The fact that action potentials could be elicited by microwave radiation at frequencies of 10 or 30 GHz, as well as by IR radiation and by conductive heat cells, suggested that the effect of microwave irradiation was thermal in nature.

In 1961, McAfee (*@MR0243*) reported the effects of 10-GHz pulsed microwave irradiation (1,000 pps) at 200 mW/cm^2 on the peripheral nerves of decerebrate and anesthetized cats. The nerves (sciatic, radial, or trigeminal) were exposed and focally irradiated. When the exposed nerves were heated to about 45 C by microwaves or IR radiation, an injury reflex occurred. Cooling the nerve during irradiation prevented the response. Irradiation of skin receptors (3 mm deep) produced similar results. McAfee concluded that 10-GHz microwaves can penetrate to nerve receptors in the skin and that behavioral and functional alterations are due to heating and not to a direct neurologic effect.

McAfee et al (*@MR1884*), in 1961, stated that the various neurologic effects of microwave radiation, such as changes in behavior, are due to thermal stimulation of the peripheral nervous system rather than to alteration of CNS activity by some nonthermal mechanism. In 1963, McAfee (*@MR2125*) reported that heating of exposed nerve bundles to 42±2 C by microwave (2.45 and 10 GHz) and IR radiation, warm air, warm water thermodes, and high-resistance electric wire produced identical physiologic responses in decerebrate cats. The effects included a rise in blood pressure, pupillary dilation, changes in respiration and heart rate, and a crossed extension reflex (see also (*@MR2887*)). McAfee (*@MR1973*) suggested in 1970 that neural and hormonal interactions result from heat stimulation of peripheral nerves and that so-called nonthermal microwave effects represent the consequences of that interaction.

Gordon et al (*@MR0799*), in 1963, reported the effects on albino rats of 3- and 10-GHz microwave radiation at power densities up to 10 mW/cm^2. The animals were acoustically sensitized to respond to a bell with a motor reaction or convulsive attack. Reductions in sensitivity occurred during irradiation but were not as prominent at 3 GHz as at 10 GHz and did not appear as soon. At 3 GHz, a power density of 1 mW/cm^2 was sufficient to produce a decrease in 81.6% of the animals exposed. Microscopic examination of nervous tissue revealed reversible changes in CNS structures, which disappeared within 3-4 weeks. Marked aberrations were noted in the peripheral receptor apparatus, especially following irradiation in the 30-300 GHz range. Gordon et al considered the changes observed in the skin receptors to be the result of thermal injury.

(d) Electroencephalogram and Other Central Nervous System Potentials

Taylor et al (*@MR0151*), in 1973, reported on a study devised to determine the effects of microwave irradiation on the latency of the potentials evoked in the thalami of anesthetized cats by stimulation of the peripheral sense organ. Recording microelectrodes were inserted into one lateral nucleus of the thalamus, and a thermocouple was placed in a homologous location in the contralateral hemisphere. Heating and cooling devices were then attached to the head. An electric shock to the forepaw was used to evoke thalamic potentials. Microwave radiation with a frequency of 918 MHz and at power densities of 20 and 30 mW/cm^3 was directed at the back of the animal's head from a distance of

8 cm. Changes in the evoked potentials produced by irradiation were mimicked by temperature elevations produced by the heating apparatus. Furthermore, successive application of radiation alone, radiation and cooling, and cooling alone produced a series of sequential changes in brain temperature, followed by corresponding changes in the latency of the potential. Thus, a thermal mechanism was proposed to be responsible for the variation in evoked thalamic potential. Justesen and Bruce-Wolfe (*@MR2610*) also described the effect of temperature on the latency of a visually evoked electrocortical response in rats.

Microwave-induced paroxysmal bursts, consisting of spikes or spike-wave complexes, in ECoG tracings from the frontal and occipital areas of the rat brain were described by Bertharion et al (*@MR0781*) in 1971. The effect was attributed to stimulation of the cerebral cortex through the reticular formation. Dumanskii and Shandala (*@MR1832*) noted microwave-induced synchronization of the cortical rhythms of rats in 1974. When the occipital ECoG's of 10 sham-irradiated control and 8 PW-irradiated rats were compared by Servantie et al (*@MR0291*) in 1975, a radiation-induced synchronization of the cortical neurons was observed. The rats were irradiated with pulsed 3-GHz microwaves for 10 days in an anechoic chamber under far-field conditions. The pulse width was 1 µs, the pulse repetition frequency about 550 pps, and the power density 5 mW/cm^2. Measurements were made outside the irradiation chamber after the generator had been switched off; thus, artifacts were unlikely. The synchronization lasted for 1-2 minutes and suggested a direct action of the electromagnetic field on cerebral neurons.

Gvozdikova et al (*@MR1551*) noted changes in the occipital EEG's of 172 rabbits irradiated for 5 minutes with SHF microwaves at 0.02, 0.08, 0.4, 2, 10, and 50 mW/cm^2. In general, four different responses were observed: a slowing of the basic rhythm with a simultaneous increase of amplitude, the converse, a decrease in amplitude alone, or no change. All four responses were observed after irradiation with 0.3-, 0.577-, and 2.4 GHz microwaves, and the relative proportion of each appeared to be independent of power density. The shortening in the latent period of the EEG response by irradiation was found to be a linear function of increasing power density. Furthermore, irradiation at the lowest frequency tested, 0.3 GHz, produced the shortest latency.

Baranski and Edelwejn (*@MR0851*), in 1967, reported on a series of EEG examinations of rabbits irradiated with microwaves. In general, the multiple exposure conditions produced only negligible rises in temperature, and irradiation with 10-GHz microwaves caused no EEG or morphologic alterations. Multiple exposures to PW 3-GHz microwaves produced desynchronization in the recording from the primary motor region and slow waves and spikes in recordings from the optic cortex. After long-term irradiation with CW 3-GHz microwaves, the amplitude of the EEG had diminished to near zero, and similar, but less extensive, morphologic changes were evident. The absence of congestion or posthemorrhagic and hemocytorrhagic focuses, as well as of elevation in tissue temperature, indicated that changes observed with long-term PW irradiation were not thermally induced. Single exposures to 3-GHz radiation led to increases in rectal, subcutaneous, and cortical temperatures that rose with the incident power density; for example, the rise in the temperature of the brain surface amounted to 2.5 C at 30 mW/cm^2 with pulsed irradiation and 4.5 C with continuous irradiation. The results suggested to Baranski and Edelwejn that low-level (5-10 mW/cm^2) long-term irradiation had a cumulative effect and that the lack of any observable changes with higher frequency (10 GHz) microwaves was due to shallow penetration.

Beagles irradiated with CW 2.45-GHz microwaves at 88 and 176 mW/cm^2 showed no changes in behavior but definite changes in EEG, according to a 1972 report by Lambert et al (*@MR1180*). Eight days after behavior testing, EEG and ECG tracings were made. Frontal and occipital EEG's were recorded, and visual and auditory responses were elicited before, during, and after a 20-minute irradiation of the heads of anesthetized dogs. In comparison with preirradiation patterns, irradiation increased the strength of and synchronized the EEG traces from two areas of the cortex. This effect was interpreted as an indication of arousal. Latency and amplitude comparisons of the evoked visual and auditory potentials demonstrated, on the other hand, no microwave effect.

Bychkov and Dronov (*@MR2634*) reported results of short-term microwave irradiation (frequency not specified) of rabbits at nonthermal (100 $\mu W/cm^2$)

power densities in 1974. They measured parallel changes in background activity of the cerebral cortex, reticular formation, and posterior hypothalamus. Separate long-term experiments were carried out on the interactions between the anterior and posterior hypothalamus. A total of 24 rabbits was used. After a 30-minute exposure, deactivation was found to predominate over activation in the hypothalamus and cortex but not in the brain stem. Bychkov and Dronov, having noticed a direct functional correlation between changes in the cortex and changes in the hypothalamus (eg, inhibition in one was correlated with inhibition in the other), concluded, therefore, that the hypothalamus may be involved in the cortical responses to irradiation with microwaves. Antagonistic responses between the hypothalamus and reticular formation sometimes prevented the manifestation of SHF radiation effects on the cortex.

According to Bychkov and Dronov (*@MR2634*), there was a generalized deactivation in the hypothalamus after 1-2 weeks of irradiation. In general, the posterior hypothalamus displayed deactivation before the anterior portion did. Phasic evolution of responses to microwaves was also observed. After 1-2 weeks of irradiation, cumulative effects were not apparent at the power densities used. The data supported the notion of diencephalic genesis of the syndrome induced by microwave irradiation.

Faitel'berg-Blank and Perevalov (*@MR3044*) described in 1978 RF-induced changes in nerve cell activity in the brains of 34 chinchilla rabbits. Total and pulsed activities were monitored with implanted microelectrodes after

10 minutes of exposure of the head to 460-MHz radiowaves. Irradiation at a power density of 2 mW/cm^2 activated the EEG, facilitated assimilation of the rhythm of light flashes at 13-25 Hz, and increased the frequency of nerve cell spiking; irradiation at 5 mW/cm^2, on the other hand, increased the synchronization of electric activity, hindered assimilation of the rhythm of light flashes, and decreased the discharge frequency of the cerebral nerve cells. The hippocampus and hypothalamus were more sensitive to RF irradiation than was the thalamus. Faitel'berg-Blank and Perevalov surmised that the EEG effects had a nonthermal origin, since a power density of 40 mW/cm^2 is required to raise brain temperature 0.1 C.

Bychkov et al (*@MR2668*) discussed the effects on rabbits of long-term irradiation in 1974. The experiments were designed to simulate industrial exposure conditions. The total irradiation time of 1 hour included exposures to 3-GHz microwaves at several power densities ranging from 60 to 320 μW/cm^2. Rest periods (no irradiation) totaling almost 1 hour were interspersed between the intermittent exposures. Irradiation lasted for 2 months. Electroencephalographic patterns recorded from this group of 12 rabbits were compared with those from a second group irradiated at 153 μW/cm^2 for 1 hour (total energy density and exposure duration similar to the first group) and with those from a third group of eight control rabbits sham irradiated for 2 months. By integrating the length of, and the period between, the slow and rapid fluctuations in EEG activity, Bychkov et al were able to show that both microwave irradiation conditions produced transient responses: desynchronization in 44% of the rabbits and synchronization in 43%. Recovery, however, to the preirradiation pattern required 1 week longer after the intermittent regimen. This observation, plus the more persistent transient processes and amplification of nonlinear potentials noticed with the intermittent irradiation, implied a more severe biologic effect of simulated industrial exposures.

Frey (*@MR1839*) observed in 1967 that evoked potentials from the brain stem distinct from cochlear microphonics occurred in cats irradiated with PW microwaves. The minimum power density required to evoke a potential was 30 μW/cm^2 average and 60 mW/cm^2 peak. Variation in the repetition frequency (12, 24, 36, 80, and 130 pps) was not critical so long as peak power did not fall below the threshold value. No correlation of the functional effects of such potentials was attempted except to mention the extremely low power densities involved.

Direct stimulation of electric activity in the brain by RF irradiation had been mentioned as possible by Baldwin et al (*@MR0843*) in 1960. Bawin et al (*@MR0768*), in 1973, reported that VHF fields, at low power densities and amplitude modulated at biologic frequencies, could affect the production of specific transient brain rhythms in operantly conditioned cats as well as reinforce the rate of occurrence of several spontaneous rhythms. To monitor ECoG and electro-oculogram activities, bipolar electrodes were implanted at several locations (caudate nucleus, amygdala, nucleus ventralis anterior of the thalamus, centrum medianum, hippocampus, midbrain reticular formation, and presylvian gyrus) in 12 adult female cats. For irradiation, each cat was placed with its longitudinal axis parallel to the field plates, which were firmly attached to the floor of a copper-screened, wooden isolation booth. The cats were trained to respond to light flashes on an operant-conditioning schedule, with negative reinforcement as the unconditioned stimulus.

Trained and untrained animals were compared during periods of overtraining and extinction for their response to sham irradiation or irradiation with 147-MHz radiation at 1 mW/cm^2 and below (*@MR0768*). Only when the field was amplitude modulated at frequencies of 1-25 Hz were there observable effects on the patterns. The irradiated cats differed from controls in the rate of performance (greater regularity of patterns), accuracy of the reinforced patterns (sharper frequency bandwidth), and resistance to extinction (minimum of 50 days vs 10 days; one performance session per day). The positive aspect of RF irradiation was also evident from experiments on the enhancement of frequency-related spontaneous biologic rhythms. Generalized thermal effects were ruled out, since the power densities involved were less than 10% of accepted thermogenic levels.

In 1976, McRee et al (*@MR1952*) reported that microwave irradiation at power densities between 1 and 20 mW/cm^2 had no effect on synaptic transmission in the spinal cord. Adult cats were functionally decapitated by having the blood supply to the brain obstructed. This technique allowed the spinal cord to be studied under drug-free conditions. Electrodes were connected to the sciatic nerve and the ventral root of the seventh lumbar segment for stimulation and recording, respectively, of externally generated neural potentials before, during, and after CW irradiation at 2.45 GHz. The E-field was perpendicular and the H-field parallel to the cord during each exposure, which generally lasted 30 minutes. McRee et al interpreted the results as indicating thermal interaction of microwave radiation with the spinal cord.

In a 1974 analysis of electrophysiologic effects of electromagnetic fields in the RF and microwave range on animals, Guy et al (*@MR0089*) also discussed thermal mechanisms. In vivo irradiation of anesthetized cats was done at far-field conditions with 918-MHz and 2.45-GHz CW radiation. Incident power densities of 1.3-52 mW/cm^2 were used, and the measured power absorbed at the brain surface and thalamus was 0.6±0.2 and 1.88 mW/cm^3, respectively. The total incident energy was kept constant at 1.0 mWh/cm^2 (corresponding to an SAR of 0.78 Wh/kg). Decreases in latency and a reduction in amplitude or abolition of evoked potentials in the brain and spinal cord were observed during irradia tion. The threshold occurred at an absorbed power between 2.5 and 5.0 W/kg, which corresponded to an incident power density of 5-10 mW/cm^2 on a cat head and of 10-25 mW/cm^2 on a human head. Temperature increases produced in the thalamus by irradiation were similar to those produced by circulating heated fluid through a heat exchanger at the base of the skull, and all phenomena observed to occur during microwave irradiation could be simulated by conductive heating.

(e) The Auditory Response

The perception of RF radiation as sound has been referred to as the "auditory response," and several alternative mechanisms have been proposed to account for the effect. Frey (*@MR1627*) suggested in his 1962 description and analysis of the auditory effect that microwave radiation could interact with the electromagnetic fields of neurons. Observations on normal and deaf volunteers indicated that hearing depended on the frequency and the peak power density of the radiation. The perception of UHF radiation was described in more detail by Frey (*@MR0711*) in 1963. He studied the threshold power density required for auditory detection of four frequencies from the RF portion of the electromagnetic spectrum (216 MHz - 2.98 GHz). Exposures at average power densities of less than 10 mW/cm^2 were sufficient to elicit an auditory response; however, the decisive factor in perception was the peak power density. The minimum detected signal had a peak power density of 229 mW/cm^2 and field strength of 13 V/cm. Irradiations at frequencies of 425 MHz and 1.3 GHz were perceived at average power densities of 3.2 and 0.4 mW/cm^2, respectively. Frey suggested that the effect could be attributed to direct stimulation of neurons in the temporal lobe of the brain by electromagnetic energy, although he offered no definitive proof.

Constant (*@MR0544*), in 1967, described the testing of three human subjects for their abilities to hear radiation at 3, 6.5, and 9.5 GHz. The individuals were placed in an anechoic chamber in such a way that one of their temporal lobes was normal to the axis of propagation of a pulsed microwave signal at an average power density of 5 mW/cm^2. Pulse widths of 0.5 μs or shorter were not perceived; pulse repetition rates greater than 100 pps produced the sensation of a buzz, whereas rates less than 100 pps were perceived as individual pulses. A frequency of 9.5 GHz was not perceived. The sensations were reported to vary with the pulse repetition frequency.

In 1972, Frey et al (*@MR0704*) reported a psychophysical study of the RF sound phenomenon in which the more subjective aspects of RF hearing were discussed and analyzed. Pulsed RF radiation with pulse widths between 2.5 μs and 2.0 ms and pulse repetition frequencies between 1 and 400/s was perceived as buzzing, clicking, or hissing sounds originating within or behind the head. The position of the head in the field did not affect perception, although the temporal area was the most sensitive region. The preliminary threshold data indicated that the peak power required for sensation was at a minimum, ie, 300 mW/cm^2, between frequencies of 0.4 and 1.5 GHz. Frey et al ruled out electrophonic phenomena, radiation pressure, and cochlear microphonics as mediating mechanisms of the auditory response.

The 1972 report (*@MR0704*) also described studies with subjects irradiated in an anechoic chamber with pulsed microwave energy at a carrier frequency of 1.2 GHz. The direction of polarization did not affect the results. In tasks involving a comparison of pairs of RF sounds, relative loudness could be unequivocally distinguished by 14 untrained subjects when peak power served as the dependent variable. Varying the pulse repetition frequency resulted in the perception of sounds with pitch and timbre. An analysis of RF sound to determine whether it could be characterized by certain acoustic energy variables was unsuccessful. In their 1973 psychophysical study, Frey and Messenger (*@MR0703*) subjected four trained observers to pulsed UHF illumination in an RF anechoic chamber. The minima of peak power and pulse width required for hearing were 80 mW/cm^2 and 20 μs. The data suggested, furthermore, that a maximum pulse width existed, thereby defining an optimal band for perceived loudness. In discussing the mechanism of the effects, Frey and Messenger stated that their data supported neither a hypothesis of radiation pressure conveyed by bone conduction from skin to ear, since the energy available was far below the conduction threshold, nor one involving radiation pressure against the tympanic membrane or round window.

Sommer and Von Gierke (*@MR1393*), in 1964, cautioned against acceptance of Frey's (*@MR1628*) early hypothesis of direct cortical or nerve fiber stimulation by RF fields. Calculations made for electrostatic fields at audiofrequencies were extrapolated to wavelengths at which electromagnetic radiation pressure becomes significant. Sommer and Von Gierke concluded that direct electromechanical excitation of the bone or tissue outside the cochlea was probable. Air conduction and normal cochlear perception, which they found to occur at 1-10 kHz, then transpired.

In 1974, Taylor and Ashleman (*@MR0152*) analyzed the auditory effect in cats. Electrodes were implanted in anesthetized cats so that potentials could be recorded from the eighth cranial nerve, the medial geniculate nucleus, and the primary auditory cortex. Acoustic pulses, 10 µs in width at a rate of 1 pps, were presented first to ensure that the expected response was being recorded and to establish minimum and maximum levels. Microwave stimuli consisting of 32-µs pulses of 2.45-GHz energy at a repetition rate of 1 pps were then substituted. The horn radiator was positioned at an angle of 30° from the sagittal plane and at a distance of 10 cm from the rear of the skull. Responses evoked in the three regions were similar for both acoustic and microwave energies. This suggestion of a common effect of acoustic and microwave stimuli on the periphery of the nervous system was further verified by the complete disappearance of both evoked potentials after destruction of the cochlea, which demonstrated the lack of direct nerve excitation.

Chou et al (*@MR0397*), in 1975, reported recording 50-kHz oscillations at the round windows of the ears of guinea pigs during irradiation with PW 918-MHz microwaves at pulse widths of 1-10 µs and a repetition rate of 100 pps. The experiments were performed under near-field conditions, and the far-field equivalent energy density was estimated to be in the range of 0.05-3.32 mJ/cm^2. The average absorbed energy per pulse was 1.33 J/kg. Because the signals occurred immediately on stimulation, preceded the auditory nerve's response, and were also present up to 200 µs after the end of the stimulus, Chou and colleagues interpreted their data as indicating that a mechanical disturbance of the hair cells of the cochlea produced the so-called cochlear microphonic. The size of the oscillation was the same function of absorbed microwave energy and of sound pressure, further suggesting that microwave radiation is an acoustic stimulus. Chou et al (*@MR0336*), in 1976, showed that pulsed micro-waves also induce cochlear microphonics in cats. The fact that the oscillation frequency depended on the size of the skull offered support for the hypothesis that the auditory effect was a mechanical disturbance created by thermal expansion pressure generated within the skull.

Further proof for microwave-initiated mechanical activation of the auditory system at the cochlear level was presented in 1977 by Chou et al (*@MR1997*). Varying the pulse width (10, 5, and 1 µs), the polarization of the field, and the carrier frequency did not alter the frequency or duration of the response. The only correlation observed was an inverse relation between the frequency perceived and the length of the cranium. Minimum energies required to produce a response were 10 mJ/kg in cats, 2.5 mJ/kg average in kittens, and 7.5 mJ/kg average in guinea pigs. Chou et al considered these values to be consistent with a previous estimate for a peak threshold energy in humans of 16 mJ/kg.

In 1978, Cain and Rissmann (*@MR3042*) reported that the hearing threshold for 3-GHz microwave pulses 5, 10, and 15 µs in width was between 2.3 and 20 $\mu W/cm^2$ for humans, beagles, cats, and chinchillas. Data obtained from standard audiograms and binaural hearing tests with humans were interpreted as indicating a strong correlation between the microwave hearing thresholds and the thresholds for hearing air-conducted acoustic signals above a frequency of 8 kHz.

Rissmann and Cain (*@MR0374*) reported that the threshold for hearing PW 3-GHz radiation was dependent on energy density rather than on peak power per pulse. Pulse widths of less than 20 μs were detected by cats, beagles, and chinchillas if the average energy density was 8.8 $\mu J/cm^2$; for humans, the threshold average energy density was 10.5 $\mu J/cm^2$. The threshold level for producing an audible sensation by a single short microwave pulse is five orders of magnitude below 1 mWh/cm^2, or 3.6 J/cm^2, and therefore far below average power densities known to be thermogenic to man, according to Guy et al (*@MR1648*). In their analysis of the electromechanical mechanism responsible for the auditory effect, Guy et al reported in 1975 that audible clicks could be detected by human observers irradiated with pulsed 2.45-GHz microwaves at a threshold incident energy density of approximately 40 $\mu J/cm^2$ and a threshold specific energy density absorption rate of 16 mJ/kg/pulse. All experiments were performed in a shielded room, and the microwave horn was placed directly behind the subject's head within the near field. Pulse width was an important variable, whereas the effect appeared to be independent of peak power density as had been suggested by Frey and Messenger (*@MR0703*). Similar measurements made with cats yielded approximately the same results when the frequency was lowered to 918 MHz. At still higher frequencies, ie, radiation between 8.67 and 9.16 GHz, the threshold incident energy densities increased to 20 times those at a frequency of 918 MHz. The effect was considered to depend, therefore, on the size of the skull as well as on the pulse width and the repetition frequency. This suggested to Guy et al that electromagnetic energy was being transduced into acoustic energy due to thermal expansion. Furthermore, the evoked potentials were similar to those stimulated by acoustic clicks from a speaker and by a piezoelectric transducer attached to the skull, which represent conduction of conventional sound stimuli by air and bone, respectively.

Johnson et al (*@MR2771*) reported in 1976 that rats trained to respond with a nose poke to a 7.5-kHz acoustic cue would respond similarly when 918-MHz radiation was substituted. Both pulsed signals had a pulse repetition rate of 10 pps; however, the acoustic signal had a pulse width of 3 µs, whereas the RF signal had a pulse width of 10 µs. The average power density of the RF field was 15 mW/cm^2, which yielded an energy density per pulse of 150 µJ/cm^2.

A neurophysiologic analysis of the response of cat auditory neurons to pulsed 915-MHz radiation was reported by Lebovitz and Seaman (*@MR0161, @MR2004*) in 1977. Cats were anesthetized and immobilized, and a fluid-filled recording electrode was placed directly into the proximal portion of the eighth cranial nerve. All experiments were performed in an electrically shielded, absorber-lined chamber, with microwave radiation being directed toward the dorsolateral aspect of the cat's skull. Pulse durations of 25-300 µs and repetition rates below 10 pps were effective in producing a response at average power densities of 1 mW/cm^2 or below. In general, the evoked potentials were independent of the average rate of energy absorption: The SAR never exceeded a calculated value of 0.5 mW/g for the medulla, and the threshold for inducing a response occurred at an energy dose of 4 μJ/g/pulse. The response to the microwave stimulus was compared with that elicited by acoustic clicks applied by a pulse-driven condensor earphone connected to a hollow ear bar of the stereotaxic apparatus. The potentials evoked by pulsed microwaves and acoustic clicks were similar in form, although the latency periods for the former were uniformly shorter. These results indicated that (1) the mechanical properties of the basilar membrane were basic to both microwave and acoustic responses, (2) hair cells or auditory nerve fibers were not activated directly, (3) mechanical factors within the cochlea were involved similarly in determining the microwave and acoustic responses, and (4) the microwave-acoustic stimulus originated within the cat's head. Thus, the data were most consistent with electromechanical activation of the auditory periphery. Cochlear microphonics might be secondary to the thermoacoustic phenomenon, according to Lebovitz and Seaman.

In a comparison of several energy transduction mechanisms that might be responsible for evoking an auditory response in human subjects to microwave radiation, Lin (*@MR1695,@MR1696*), in 1976 and 1977, concluded that thermoelastic phenomena (see Foster and Finch (*@MR0695*)) are the most likely processes. The stresses resulting from radiation pressure and electrostrictive force were found to be much too small, in relation to those generated by volume heating of the brain tissue, to have any effect.

Microwave radiation was shown by Zyss and Boczynski (*@MR1521*) in 1972 to induce morphologic changes in the organs of Corti of guinea pigs. Eighty guinea pigs were irradiated with 3-GHz microwaves for 4 h/d for 50 days at 2 mW/cm^2. The internal and external ciliated cells of the organ of Corti were swollen, vacuolar degeneration of the cytoplasm was evident, the nuclei were pycnotic and swollen, and the concentrations of glycogen and of nucleic acids were reduced. The changes were more evident in basal cells on the 50th, and final, day of irradiation than they were on the 25th day. After a 30-day recovery period, much of the damage had regressed. Zyss and Boczynski considered the reversible changes to be indicative of metabolic disorders in the cells capable of affecting the bioelectric activity of the organ.

During a 1968 survey of workers who had been exposed to UHF fields on a long-term basis, Chalov (*@MR0509*) found only slight alterations in otorhinolaryngeal functions and no pathologic changes in the organs. Two groups were exposed--one comprised 46 persons irradiated irregularly at 10-100 $\mu W/cm^2$ from a few minutes to 2 h/d, and the other comprised 51 persons exposed at 15-38 $\mu W/cm^2$ on a regular basis--and compared with unirradiated control groups. Comparisons between the findings of examinations made immediately after periods of possible exposure and after an 8- to 10-hour rest period indicated that the acuity of olfaction improved slightly, that the sensitivity thresholds of the vestibular apparatus did not change, and that the threshold of speech discrimination increased twofold. Chalov hypothesized that the observed changes were due to a direct effect of the UHF field on neurons.

Behavioral Effects

Alterations induced in the spontaneous and learned behaviors of animals by RF and microwave radiation are listed in Table III-8. In addition to the reports discussed in this section, several related studies are described in the section entitled General Physiologic and Other Effects.

(a) Spontaneous Activity

In a preliminary experiment observing the spontaneous activity of rats, Eakin and Thompson (*@MR0644*) described in 1962 the discovery of a significant difference between control and multiply irradiated animals. Through the use of a sweep generator to produce frequencies between 450 and 965 MHz, groups of five rats were irradiated for 30 or 60 min/d. The same technique was used by Eakin and Thompson (*@MR0645*) in a more comprehensive study, published in 1965, in which 10 male rats were irradiated for 47 consecutive days with a continuous range of frequencies between 300 and 920 MHz. The sweep took 82 seconds, and the power level was maintained at a constant 50 V. Several

TABLE III-8

BEHAVIORAL EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse (24)	0.8	43	2 h/d, 5 d/wk, for 35 wk	No change in voluntary motor activity	Spalding et al (*@MR2826*)
Mouse (28)	0.915	5 mW/g (environmentally controlled exposure chambers)	8 h/d on alternate days for 2 mo	Initial reduction in absorption noted over short term (*@MR1660*) replaced by increase over long term	Ho et al (*@MR2351*)
Mouse (94)	2.38	1, 10	2 h/d for 1-35 d	Motor conditioning altered, ie, irradiation deconditioned learned behavior (swimming); learning (to swim) inhibited by irradiation	Gusarov (*@MR2325*)
Mouse (32)	2.45	23.6, 31 mW/g (comparison of animals constrained and free to move in environmentally controlled chambers)	30 min	Decrease in oxygen consumption induced by irradiation similar in both groups; decrease in absorption (SAR) due to reorientation with respect to field	Ho and Edwards (*@MR1660*)
Mouse (5)	2.45 (CW)	46 mW/g at output power of 2.7 W (free movement within holder in environmentally controlled waveguide exposure chamber)	--	Consistent avoidance or escape response rates maintained with microwave radiation as stimulus	Monahan and Henton (*@MR1725*)
Mouse (102)	2.45	--	20 min	20% decrease in SAR during irradiation (reorientation to reduce absorption)	Monahan and Ho (*@MR1992*)
Rat (10)	0.45-0.965 (sweep)	--	30, 60 min/d for 20 d	Change in spontaneous activity by 12th d	Eakin and Thompson (*@MR0644*)
"	0.3-0.92 (sweep)	50 V	47 d	Decrease in spontaneous activity observed on 30th-40th d	Eakin and Thompson (*@MR0645*)

TABLE III-8 (CONTINUED)

BEHAVIORAL EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat (18)	0.32-0.45 0.77-0.9 (sweep)	0.43-0.15 mW	21 d	Decrease in spontaneous activity inversely related to frequency	Korbel and Fine (*@MR1869*)
Rat (11)	0.4-0.7	5-20	55 min maximum	Time to work stoppage inversely related to heating and to power density, greatest effect at resonance 0.6 GHz	D'Andrea et al (*@MR1608*)
Rat (3)	0.6 (PW)	170 (peak); 0.51, 5.1 (average)	"	"	"
Rat (21)	0.22-0.50	25	10 min	Time to work stoppage least and rise in colonic temperature greatest with E-field polarized parallel to long axis of rat and at frequencies near 0.5 GHz	D'Andrea et al (*@MR2077*)
Rat (140)	0.05	0.5-6 V/m	10-12 h/d for 180 d	Disturbance of conditioned reflex	Serdiuk (*@MR2518*)
Rat (10)	0.0697	150 V/m	60 min/d for 4 mo	Temporary degradation of conditioned reflex, ie, increase in and decrease in cue differentiation ability	Lobanova and Goncharova (*@MR2421*)
Rat (32)	0.915	7, 10, and 17 mW/g at 5, 9.1, and 19 W output power (restrained in Plexiglas holder in environmentally controlled waveguide)	15 min	Decrease in rate of energy absorption with time of irradiation at 2 higher output powers; taste aversion to sucrose not acquired	Monahan and Henton (*@MR1726*)
Rat (8)	0.918	10	10 h/d for 3 wk	Reduction in motor activity	Moe et al (*@MR2274*)

TABLE III-8 (CONTINUED)

BEHAVIORAL EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat (9)	0.918	10-40 (far field)	--	Transient effect (1 d) on head-raising response at 40 mW/cm^2	Lin et al (*@MR1697*), Caldwell et al (*@MR0244*)
Rat (6)	0.75-3	25-150	--	Time to work stoppage function of power density and frequency	Hawkins et al (*@MR0094*)
Rat (16)	(1) 1.2 (PW)	(1) 0.6 (av) and 200 (peak)	--	Rats avoided PW radiation by moving from unshielded to shielded half of shuttle box.	Frey and Feld (*@MR0707*)
	(2) 1.2 (CW)	(2) 2.4			
	(3) 1.2 (PW)	(3) 0.2 (av) and 2.1 (peak) (anechoic exposure chamber, E-field horizontally polarized)			
Rat	(1) 1.3 (PW)	(1) 0.2 and 0.65 (av) and 0.4 and 1.3 (peak)	--	(1) Pain-induced aggressive behavior less intense in irradiated animals	Frey (*@MR2944*)
	(2) 1, 1.3, 1.5 (PW)	(2) 0.005-0.2 (av) and 0.05-0.2 (peak)		(2) Degree of docility dependent on peak power	
	(3) 1, 1.3, 1.5 (PW)	(3) 0.2 and 1.4 mW/cm^2 (av) and 0.4 and 2.8 mW/cm^2 (peak) (anechoic chamber used for irradiation and testing)		(3) Adverse effect on motor coordination and balance	
Rat (15)	2.45	2.3 mW/g	5 h/d for 110 d	Increase in locomotor activity, decrease in operant visual discrimination	Mitchell et al (*@MR1991*)

TABLE III-8 (CONTINUED)

BEHAVIORAL EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	2.45 (PW)	6 and 11 mW/g	--	Temporary decrease in exploratory activity, swimming, and discrimination	Hunt et al (*@MR0221*)
Rat (6)	2.45 (PW, 12- and 60-Hz modulation)	2.5-15	60 min/d for 124 d	Decrease in rate and number of conditioned reflexes with exposure, no microscopic damage to brain tissue	Justesen and King (*@MR1676*)
Rat (3)	2.45 (12- and 60-Hz modulation)	0.5-6.4 mW/g	--	Irradiation 50% as efficient as acoustic pulse in suppressing operantly conditioned response	King et al (*@MR0871*)
Rat (10)	2.45	50	20 min	Increase in maze learning	Nealeigh et al (*@MR1146*)
"	2.45	2-4	8 h/d for 14 d	Differences in learning (Skinner box) by 5th day	Campbell and Thompson (*@MR2268*)
Rat (12)	2.45	1-15	1 h/d for 6 d	Change in lever-press routine learned on DRL (low rate of performance) at 15 mW/cm^2	Diachenko and Milroy (*@MR0076*)
Rat (4)	2.45 (CW), 2.86 (PW), 9.6 (PW)	2.5-20	30 min/d for 1-2 d/wk	Increase in learning for low performance rate conditioning, decrease for high performance rate	Thomas et al (*@MR0051*)
"	2.45	8.8-37.5	1 h/d	No effect on low-baseline rate performance, decrease in high-rate performance at 37.5 mW/cm^2	Sanza and de Lorge (*@MR1759*)
Rat (228) and rabbit (60)	(1) 0.05 (CW) (2) 2.5 (CW)	(1) 0.0006-10 $\mu W/cm^2$ (2) 0.5-10 $\mu W/cm^2$	(1) 10-12 h for 120 d (2) 8 h for 120 d	Power densities between 1.9 and 10 $\mu W/cm^2$ in case 1 and between 5 and 10 $\mu W/cm^2$ in case 2 altered conditioned reflex activity.	Dumanskii and Shandala (*@MR1832*)

TABLE III-8 (CONTINUED)

BEHAVIORAL EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat (10)	3 (PW and CW)	40	15 min/d for 4 mo	Increase in latency and frequency of omission of conditioned reflex similar for PW and CW irradiation	Lobanova (*@MR2420*)
Rat (33)	3 (CW and PW) and 10.7 (CW)	0.5-2	185 h	No changes in five types of spontaneous motor activity	Roberti et al (*@MR0041, @MR0139*)
Rat (5)	3 (PW)	25	17 d	No change in runway performance or in five types of motor activity	"
Monkey (3)	2.45	10 W	20 2-min exposures/h, 1 h/d for 5 d	No effects on cue discrimination	Galloway (*@MR0018*)
Monkey (4)	2.45	1-15 W (head inserted into rectangular waveguide)	--	Decline in discriminatory ability under simultaneous irradiation and treatment with flenfluramine (serotonin "depleter") only, indicating some interaction with monaminergic processes in brain	Galloway and Waxler (*@MR2946*)
Monkey (3)	2.45	16-72	30, 60, 120 min	Decrement in performance of vigilance task observed only at 72 mW/cm^2	de Lorge (*@MR2270*)
Monkey (2)	3.2	213-736 V/m	3 h/d for 7 d	No change in performance (pilot training seat)	Farrer et al (*@MR1950*)

*Power density unless otherwise specified psychologic variables, ie, activity, emotionality, and latency of the electroconvulsive shock reaction, were measured and compared with those from sham-irradiated controls.

Eakin and Thompson (*@MR0645*) interpreted their observations as indicating less active, more emotional behavior on the part of irradiated rats. The effects were considered to be cumulative. Nonthermal mechanisms were postulated to account for the behavioral changes, since low power levels were used (power density was not measured), behavior was assessed during nonirradiation periods, and no increased water consumption was observed. In 1967, Korbel (nee Eakin) and Fine (*@MR1869*) compared the effects of low- and high-range UHF irradiation and found, in comparison with controls, a significant decrease in activity during 21 consecutive days of exposure. The lower frequencies were more effective in producing the activity change.

Chernovetz et al (*@MR1595*), in 1975, described experiments in which female mice were irradiated on the 14th day of gestation for 10 minutes at a dose rate of 38±3 mW/g with 2.45-GHz microwaves. Nine 35-day-old pups from sham-irradiated female mice were compared with 15 pups from microwave-irradiated female mice for their performance in swimming a two-alley section of a maze. No significant differences were observed between the two groups in both original and reversal learning.

The effects of microwave irradiation on the training of rats to swim were reported in 1971 by Gusarov (*@MR2325*). Irradiation for 2 h/d at 2.38 GHz and 1 and 10 mW/cm^2 antagonized the training process, ie, swimming time did not change for rats subjected to simultaneous irradiation and training for 35 days. Those rats trained to swim before being irradiated progressively lost endurance during a 25-day period of repeated daily exposures.

Two reports by Roberti et al (*@MR0041,@MR0139*) compared sham-irradiated controls with rats chronically irradiated with PW and CW 3-GHz and CW 10.7-GHz microwaves for spontaneous activity and motor ability (runway performance). All exposures were performed with vertically polarized radiation under far-field conditions within an environmentally controlled anechoic chamber. Microwave irradiation for 8 days at 0.5-2.0 mW/cm^2 produced no differences in activity, expressed in terms of six movement parameters, or of rectal temperature. Seventeen days' exposure to 3-GHz microwaves at 25 mW/cm^2 was also ineffectual. The complete lack of effect with shallow-penetrating 10-GHz radiation, even at high power levels and for long durations, indicated that any influence on superficial body structures or the peripheral nervous system is not likely to be translated into observable behavioral alterations. Spalding (*@MR2826*) also reported no change in activity during long-term irradiation.

The spontaneous behavior of rats was reported by Gillard et al (*@MR2141*), in 1976, to be altered following 2 weeks of irradiation with 9.4-GHz microwave energy. The PW field had a pulse width of 0.15 μs, a pulse repetition frequency of 2,000 pps, and average and peak power densities of 0.7 and 2.3 mW/cm^2, respectively. All exposures were in an anechoic chamber at far-field conditions; the E-field was vertically polarized. Relative to control values obtained in open-field tests, locomotor activity and emotionality did not increase but remained unchanged, exploratory activity increased more slowly, and vigilance increased initially but decreased later in the course of irradiation.

Behavioral changes in microwave-irradiated rhesus monkeys were described by Bach et al (*@MR0976*) in 1959 and Baldwin et al (*@MR0843*) in 1960. Each of 21 young rhesus monkeys was restrained in turn in a primate chair; a cylinder of copper mesh, which served as a resonant cavity for the 388-MHz radiofrequency radiation, was placed over its head. The animals were irradiated for periods ranging from 2 minutes to 3 hours, but the "usual" exposure period was 2-10 minutes. Frequencies were between 380 and 395 MHz, and estimated power densities were 12.8 mW/cm^2 over the entire head and 64 mW/cm^2 at the brain stem. During irradiation, the animals exhibited alternating periods of arousal and drowsiness, which were also recorded in EEG patterns. Weakness and paralysis were observed, as well as such eye signs as blinking and dilation of pupils and grimacing. One animal died at 2.9 minutes of exposure.

Baldwin et al (*@MR0843*) emphasized the transient nature of behavioral effects induced by microwave irradiation. Such neurologic disorders as agitation, drowsiness, akinesia, and eye signs, as well as autonomic, somatomotor, and sensory abnormalities and convulsions, were induced by irradiation. Most signs disappeared after irradiation ended; none was visible 48 hours later. A 2.9-minute exposure was lethal if the chin of the monkey was fixed in an elevated position. Rectal temperatures were increased by irradiation, but no linear dependence on exposure duration could be established. Finally, Baldwin et al observed that monkeys exposed to whole-body irradiation for 10 minutes showed none of the signs discussed above.

Frey (*@MR2944*) discussed microwave radiation-induced changes in the aggressive behavior of rats in a 1977 report. The PW 1.3-GHz radiation had a pulse width of 0.5 ms and a repetition rate of 1,000 pps. Pain-induced aggressive incidents between pairs of animals were less frequent, of shorter duration, and required more time to initiate with animals irradiated at an average power density of 0.65 mW/cm^2 and peak power density of 1.3 mW/cm^2 than with sham-irradiated animals. In other experiments, the degree of docility was found to be linearly and positively related to the peak power density, and CW irradiation was observed to be less effective than PW irradiation in inhibiting aggression.

Two experiments dealing with motor coordination and balance also were discussed by Frey (*@MR2944*). The testing consisted of several 1.5- to 2-minute trials per day in an anechoic chamber. Significant differences in motor coordination and balance were observed between sham-irradiated rats and rats irradiated with 1.3- and 1.5-GHz microwaves at average and peak power densities of 1.4 and 2.8 mW/cm^2, respectively. Irradiation at a frequency of 1 GHz at those power densities or at frequencies of 1, 1.3, and 1.5 GHz at power densities of 0.2 (average) and 0.4 (peak) mW/cm^2 produced no effects.

In 1975, Frey and Feld (*@MR0707*) described one type of behavior exhibited by rats exposed to PW radiation as "avoidance" or escape. Eight experimentally naive male rats were exposed one at a time to horizontally polarized (E-field) 1.2-GHz radiation in an anechoic chamber under far-field conditions. A shield of microwave absorber was placed between the antenna and one-half of the shuttle box into which each animal was placed for irradiation. The following power densities were used: 2.4 mW/cm^2 (CW), average 0.6 and peak 200 mW/cm^2 (PW, pulse width 30 μs, pulse repetition rate 100 pps), and average 0.2 and peak 2.1 mW/cm^2 (PW, pulse width 0.5 mg, pulse repetition rate 1,000 pps). Comparison of the statistical data indicated that rats avoided PW radiation at similar average power densities (9.2 mW/cm^2) but at peak power densities varying over almost two orders of magnitude.

The distinctive type of radiation-induced behavior described as avoidance was discussed by Monahan and Ho (*@MR1992*) in 1977. A total of 102 male adult mice was separated into 17 experimental groups and irradiated for 20 minutes with CW 2.45-GHz microwaves. The exposure chamber was an environmentally controlled waveguide that allowed the animals virtually free movement. Sixteen different forward powers were used, 4 or 5 at each of four ambient temperatures: 20, 24, 30, and 35 C. The mean SAR varied from 0.06 to

63.8 mW/g, with the higher rates used at lower ambient temperatures and lower rates at higher temperatures. Calculation of the change in the percentage of microwave energy absorbed at successive 5-minute intervals during irradiation showed that reduction of energy absorption occurred and that its magnitude depended directly on the ambient temperature. For example, at temperatures of 24, 30, and 35 C, average absorption rates of 43.5, 25.8, and 0.6 mW/g, respectively, produced 20% or more reduction in energy absorption during the fourth 5-minute interval of irradiation in comparison with that during the first 5-minute interval. No significant reductions occurred at lower rates for each of the temperature conditions. The mechanism of such avoidance was described as a change in behavior--specifically, the animals oriented their bodies relative to the source so as to reduce the incident dose of energy.

Monahan and Ho (*@MR2313*), in 1976, in another discussion of avoidance behavior, revealed that mice were capable of detecting CW 2.45-GHz radiation at average dose rates as low as 28 mW/g. The animals were tested in an environmentally controlled waveguide exposure chamber, and, by measuring integral absorbed dose, Monahan and Ho were able to calculate changes in dose rate. These changes were interpreted as being due to movement following an aversive stimulus; no visual observations were possible.

In further experiments on avoidance behavior in rats, Monahan and Henton (*@MR1725*) presented data in 1977 indicating that microwave radiation can elicit a response. The avoidance or escape response was found to be consistent throughout eight 30-minute experimental sessions with CW 2.45-GHz microwave radiation acting as the stimulus, in contrast to the low or inconsistent response rates shown by sham-irradiated controls. A systematic alteration in absorption of microwave energy dependent on ambient temperature, dose rate, exposure duration, and movement capability also was described by Monahan and Henton (*@MR1726*) in 1977. They suggested that absorbed dose did not represent another electromagnetic property of an organism, such as dielectric constant, but was a variable that could be used to characterize that organism's behavior on irradiation.

In another study on the behavior of rats in a microwave field, Ho and Edwards (*@MR1660*), in 1977, proposed that decreased oxygen consumption is correlated with a reduction in absorbed energy irrespective of any constraint on movement during irradiation. The magnitude of the decrease in oxygen consumption during 2.45-GHz irradiation was similar for animals confined to tight Plexiglas cages, as in this study, and for animals free to move (*@MR1992*). Thus, the decrease in absorption rate was presumed to be due solely to reorientation.

Results of single 15- to 30-minute exposures, such as discussed above (*@MR1992,@MR1660*), were reported by Ho et al (*@MR2351*) in 1977 as not applying to long-term exposures, ie, irradiation with CW 915-MHz microwaves for 8 h/d on alternate days for 2 months. Reductions were not observed during the 8-hour session at an average absorbed dose rate of 3.4 mW/g but were observed at one of 5 mW/g. In addition, during the 2 months, increases in the absorbed dose rate averaged throughout each 8-hour session were found to occur. Thus, the absorbed dose rate depends not only on field intensity but also on exposure duration.

In 1975, Hunt et al (*@MR0221*) reported on the degradation in performance of rats irradiated with PW microwaves. Young adult male rats were either sham or microwave irradiated for 30 minutes and then tested for exploratory activity, swimming ability, or vigilance discrimination. The 2.45-GHz radiation pulse had a half-amplitude duration of 2.5 ms and a repetition rate of 120 pps; absorbed dose rates of 6.3, 6.5, and 11 mW/g were used. During the first 30 minutes of testing at 6.3 mW/g, when hyperthermia was greatest, exploratory activity decreased slightly in microwave-irradiated rats. Swimming rates, determined by measuring the time necessary to pass through a 6-m-long alley, first decreased, then returned to preirradiation levels, and finally declined to 60% of the initial level at 24 hours after irradiation. Discrimination was tested through the use of a light flash as a positive cue (food) and a sound as a negative cue (electric shock) for a lever-pressing routine. A sixfold increase in errors was evident after irradiation at 11 mW/g. Irradiation at 6.3 mW/g produced a threefold increase followed by a rapid recovery within 20-30 minutes to sham-irradiated levels.

(b) Conditioned Behavior

In 1957, Livshits (*@MR1877*) described the results of long-term experiments on the alteration by RF irradiation of the salivary response to various stimuli in four dogs. They were exposed to 50-MHz radiation at power outputs of 7-55 W (no further information given) for 5 or 10 minutes. A decrease in the conditioned reflex (less saliva) and a deterioration in ability to discriminate among stimuli were noted following irradiation. A 1958 report by Subbota (*@MR1924*) noted that 1-2 hour exposures to SHF radiation at 5 mW/cm^2 led to variable changes in the conditioned reflex of dogs.

Serdiuk (*@MR2518*), in 1969, also reported that long-term exposure to 50-MHz radiation at an E-field strength of 0.5-6 V/m disturbed conditioned reflex behavior in rats. Similar results were described by Dumanskii and Shandala (*@MR1832*) in 1974. In those experiments, power densities of less than 10 $\mu W/cm^2$ were reported as being effective.

Lobanova (*@MR2420*) reported in 1966 that both PW and CW 3-GHz radiation at 40 mW/cm^2 produce similar increases in the latency and the frequency of omission of conditioned reflexes by rats during 4 months of irradiation. Irradiation with VHF 69.7-MHz radiation at a field strength of 150 V/m, but for 60 rather than 15 min/d, produced similar increases (*@MR2421*). Lobanova and Goncharova (*@MR2421*) also found that the conditioned reflex activity returned to normal within 20 days postirradiation.

A two-stage reaction in the feeding reflex of rats to S-band irradiation was described by Minecki et al (*@MR2902*) in 1962. The total dose given the 12 rats was varied by altering the period of exposure at one of four power densities, ie, 16, 30, 64, or 94 mW/cm^2. Inhibition of feeding began for all four power densities at a dose approximately 30 $mWmin/cm^2$ greater than that at which maximum stimulation of the reflex was observed. The dose necessary to effect a change in reflex behavior decreased nonlinearly with increasing power density.

Gordon et al (*@MR0804*) tested the effect of long-term irradiation with millimeter waves on the conditioned response of rats in 1969. Rats were irradiated at 10 mW/cm^2 for 60 min/d. After 80 irradiation sessions, the conditioned reflex to the positive stimulus (red light or sound) was absent 23±3.5% of the time. The latent period was also observed to increase. Comparisons with radiation in the decimeter (UHF range) and centimeter (SHF range) bands showed that changes induced by millimeter band (EHF range) radiation were the last to occur, were the least severe, and affected the fewest animals. An inhibition in a conditioned reflex in rats was reported by Zalyubovskaya (*@MR0749*), in 1977, following multiple exposure (60 days at 15 min/d) to 37.5- to 60-GHz radiation at 1 mW/cm^2.

The effects of periodic vs continuous exposure to 3-GHz radiation on the behavior of rats were compared in a 1968 report by Lobanova (*@MR1214*). Irradiation was for 60 min/d for 4.5 months. Periodic exposure entailed a

3-second exposure followed by 9 seconds of nonirradiation; the average power density over the 12-second period was 40 mW/cm^2, identical to that under continuous exposure conditions. The change in the incidence of conditioned reflexes increased more with periodic than with continuous irradiation during the first 60 irradiation sessions but thereafter was similar for both.

Operant conditioning involves behavior more complex than that elicited in a conditioned reflex. In 1970, Justesen and King (*@MR1676*) reported the effects of microwave irradiation on a conditioned operant response of rats. Six rats were trained to give a tongue-licking response by free-operant techniques at a fixed frequency of reinforcement of 40 (FR 40), in which every 40th response (tongue lick) was reinforced. Their behavior under nonirradiated conditions served as the immediate control situation. The rats were irradiated in an oven modified as a combination behavior-conditioning, closed-space exposure chamber with 2.45-GHz microwaves modulated at 60 and 12 Hz. The irradiation schedule provided intermittent 5-minute exposures (duty cycle of 0.5) at SAR's of 1.6, 3.2, and 4.7 mW/g. The experiment consisted of 124 daily sessions at a calculated incident power density of 2.5, 5, 10, or 15 mW/cm^2 for 60 min/d. The first 65 sessions were used for training and establishment of sham-irradiated response levels; the remaining sessions, for measurement of the responses under irradiation conditions.

The observations involved three distinct measurements (*@MR1676*). As the dose increased, the rate of licking rose but then fell, whereas the total number of responses decreased monotonically. Rats also were presented with acoustic cues during conditioning. Microwave irradiation at the lowest dose (1.5 mW/g) decreased the total number of operant responses by 32% when presented simultaneously with the tone cue. The efficiency of discrimination between the presence or absence of the tone, on the other hand, was unaffected at all doses. These data were statistically reliable, if not immediately explainable. Exposure for 20 or more minutes at a dose of 4.4 mW/g reliably increased rectal temperature by more than 2 C. Microscopic examinations of brain sections indicated no discernible effects of microwave irradiation that could be correlated with the behavioral abnormalities.

In 1971, Nealeigh et al (*@MR1146*) described a microwave-induced alteration in learning by rats. An antenna was mounted 1 m above the central starting box of a Y-maze. Ten female rats were exposed to CW 2.45-GHz radiation at 50 mW/cm^2 for 20 minutes, and then the time required to run the maze was measured. Analysis of the data indicated that the average performances of the sham- and the microwave-irradiated groups did not differ significantly during three consecutive days; however, on days 2 and 3 microwave-irradiated animals gave a higher percentage of correct responses. Nealeigh et al stated that the alteration in learning caused by irradiation resembled that produced by CNS stimulants, such as caffeine, amphetamine, and strychnine, and concluded that long-term irradiation under similar conditions would be detrimental to human performance.

In 1973, Hawkins et al (*@MR0094*) reported on the frequency and power density dependence of the effect of microwave irradiation on learning in the rat. Behavior was evaluated systematically at four different frequencies (0.75-3 GHz) and five different power densities (25-150 mW/cm^2). Three adult male and three adult female rats were trained to carry out a 15-minute lever-pressing routine on a schedule of a fixed ratio of one reinforcement for every 10 lever presses. In any given exposure session, which consisted of selecting one frequency, varying the sequence of power densities, and then moving to another frequency (the order of presentation of frequency and power were mixed for each rat), the irradiation began 3 minutes after the start of the training session and was halted after the first 1-minute interval in which fewer than 10 responses occurred. The rats were placed 1.2 m from the antenna center, with their lateral aspect normal to the direction of propagation. The E-field was vertically polarized.

A frequency of 1.7 GHz was most effective at all power densities: At 50 mW/cm^2, 10.5 minutes elapsed before work ceased, and at 150 mW/cm^2, 1.8 minutes elapsed (*@MR0094*). For a power density of 100 mW/cm^2, irradiation at 0.75, 1.7, 2.45, and 3.0 GHz halted work at 10.5, 4.0, 7.0, and 9.0 minutes, respectively. Exposure time, ie, time to stoppage, decreased monotonically with increasing power density, as did the energy density necessary to produce response termination. Frequencies of 0.75 and 3.0 GHz were least effective, and had similar effects, in stopping the lever-pressing routine (approximately 2.5 times as much energy density was required as at

1.7 GHz). Since the results were similar for all rats, and since the male rats used weighed 50% more than did the female rats, Hawkins et al suggested that microwave effects are independent of body weight. Furthermore, their results indicated the existence of increased sensitivity, with respect to the power and energy density required to produce a bioeffect, at certain frequencies.

Diachenko and Milroy (*@MR0076*), in 1975, reported on the effects of microwave radiation on performance by rats trained on a schedule known as differential reinforcement of low rate (DRL). A total of 20 rats, including twelve 90-day-old female and eight 60-day-old male rats, learned a lever-pressing routine in which they had to respond within a specific 6-second interval. Their baseline performance was then established during the 5 days following the training session, and two experiments were performed. In the first experiment, the female rats were paired in test groups and exposed one at a time to 2.45-GHz radiation at 0, 1, 5, 10, or 15 mW/cm^2 in a ventilated, screen-shielded chamber lined with microwave absorber. The rats were placed on a Plexiglas table 1.4 m directly below the ceiling-mounted horn. Each rat received, in turn, 5 days of microwave exposure for 1 h/d, 2 days of sham exposure, and a final day of microwave exposure. Performance was measured for 1 hour immediately after irradiation on each day. No significant differences between irradiated and control animals were noted except with the pair exposed at 15 mW/cm^2. However, that change was observed only on the 5th day, and performance returned to normal during the days of sham and final exposure. Diachenko and Milroy stated that this pair showed definite signs of heat stress and attributed the altered performance to heat-induced impairment of the physical ability to perform the lever-pressing task. The second experiment involved the eight male rats, which were subjected in pairs to CW radiation at 5 and 10 mW/cm^2 and to PW 12-MHz radiation with a field strength of 125 kV/m. During an exposure period of 6 days (containing two sham-irradiation periods), no difference in response was noted.

The data indicated that CW microwave irradiation at 10 mW/cm^2 or less and PW microwave radiation at 125 kV/m had no effect on an operant behavior with low work-rate performance (*@MR0076*). Based on a comparison of their results with those from previous behavioral studies, Diachenko and Milroy proposed that small thermoregulatory shifts caused by lower power densities would be more likely to affect performance requiring a high rate of work and that the effect would be independent of the relative complexity of the task. They also suggested that simple, intermediate, and complex levels of behavior may be differentially affected by microwave irradiation.

Campbell and Thompson (*@MR2268*), in 1975, reported that repeated irradiation with 2.45-GHz microwaves at power densities between 2 and 4 mW/cm^2 affected discriminatory learning behavior in rats. Twenty male rats were trained in a two-level Skinner box, and half of the animals then were irradiated for 8 h/d for 14 consecutive days before testing. Differences in performance reportedly became evident by the 5th day of irradiation, but no quantitative results were presented.

Microwave irradiation produced differential alterations in the conditioned responses of rats, according to a 1975 report by Thomas et al (*@MR0051*). Four young male rats were trained to press a lever to obtain a food pellet under a multiple reinforcement schedule, comprising a random alternation of a fixed-ratio schedule with a frequency of reinforcement of 20 (FR 20) and a DRL schedule where the first lever response had to be followed 18 seconds later by the second (or food-producing) response (DRL 18). The rats were individually irradiated for 30 minutes with either PW 2.86- or 9.6-GHz radiation or CW 2.45- or 2.86-GHz radiation under far-field conditions. Pulse width was 1 μs, repetition frequency was 500 pps, and power densities of 2.5, 5, 10, 15, and 20 mW/cm^2 were used. Each rat's baseline, ie, nonirradiated, performance served as the control. In general, the low baseline response rates under the delayed-response schedule increased by 10-20% after irradiation, whereas the high rates produced by the fixed-ratio schedule decreased by 20-50% after irradiation. Power densities between 5 and 15 mW/cm^2 produced the greatest effects. The study emphasized the dependence of performance, and hence of any radiation-induced modification, on training schedule.

Using microwave radiation of several frequencies and power densities, D'Andrea et al (*@MR1608*), in 1977, were able to show that the time to work stoppage in rats was inversely related to the increase in core temperature following irradiation. This increase, in turn, was inversely related to power density and was greatest at a frequency near resonance for the rat--specifically, 600 MHz for a rat oriented with its long axis parallel to the E-field vector. The rats were trained to perform a lever-pressing routine while restrained in a Plexiglas cage. For irradiation, the cage was placed within a microwave absorber-lined chamber located 143 cm from a single monopole antenna (far-field condition). Rectal temperature was monitored during training and irradiation sessions. Each of five rats was exposed to CW 400-, 500-, 600-, and 700-MHz radiation presented in random order at 20 mW/cm^2. A second group of six rats was irradiated with CW 600-MHz radiation at 5, 7.5, 10, and 20 mW/cm^2, again presented in random order. Three rats of the second group were also used for subsequent irradiation with PW 600-MHz microwaves at a peak power density of 170 mW/cm^2. Results were expressed in terms of mean latency to work stoppage, although the maximum period of irradiation was stated to be 55 minutes. The latency was a minimum for CW 600-MHz radiation at 20 mW/cm^2, which produced a maximum rate of temperature increase of 0.085 C/min. There was no significant effect of pulsed radiation on behavior.

The dependence of behavior on orientation of the body to the incident electromagnetic field was described by D'Andrea et al (*@MR2077*) in 1976. Rats were exposed in an anechoic chamber under plane-wave conditions. The power density was maintained at 25 mW/cm^2, and each rat was irradiated for 10 minutes at each of 20 frequencies between 220 and 500 MHz. This procedure was repeated four times with the rat parallel to the E-field; only 3 of the 20 frequencies were used with the rat parallel to the H-field or to the direction of propagation. The greatest rates of elevation in colonic temperature, and hence the greatest absorbed dose rates, were observed at 360, 440, and 500 MHz for E-field polarization. The rates of temperature increase for the other orientations were approximately 0.1 as great. Measurements of the time to work stoppage in a lever-pressing routine also indicated that a frequency of 500 MHz was most efficient in halting the behavior and that orienting the rat parallel to the direction of propagation was less efficient than orienting the rat parallel to the E-field. The time to stoppage was related to the rise in colonic temperature, and heat stress was evident at 500 MHz.

The operant behavior of rats irradiated with 2.45-GHz microwaves was described by Sanza and de Lorge (*@MR1759*) in 1977. A microwave-transparent conditioning chamber was constructed specifically for training and measurement of performance of a lever-pressing routine. The chamber was placed within an absorber-lined, environmentally controlled enclosure. The E-field was polarized parallel to the long axis of the chamber. Two rats that had high baseline rates of response were compared with two others with low baseline rates. A significant decrease in response rate and an increase in the delay of response were observed only with the high-performance pair irradiated at 37.5 mW/cm^2. A decrease in ambulatory activity, which Sanza and de Lorge associated with heat stress, was also noted in all rats irradiated at 18.4 and 37.5 mW/cm^2.

Several temporary effects on the operant behavior of rats following microwave radiation at 10-40 mW/cm^2 were described by Caldwell et al (*@MR0244*) in 1974 and by Lin et al (*@MR1697*) in 1977. Female rats were trained to perform a head-raising response for a food pellet. Training, behavior measurements, and irradiation were conducted while the rats were immobilized in acrylic cages (to prevent the formation of "hot spots"). The rats were irradiated with 918-MHz microwaves under far-field conditions in a temperature-controlled, anechoic chamber. During irradiation for 30 minutes at 10, 20, and 32 mW/cm^2, no changes in response relative to control preirradiation values were observed. Physiologic signs of heat stress were evident with irradiation at 40 mW/cm^2, and the animals' performance levels were diminished. However, the performance of rats irradiated for 30 min/d for 1 day, on three alternate days, or for five consecutive days at 40 mW/cm^2 recovered to baseline levels on the 1st day following the final exposure. These observations, plus results of experiments in which performance was measured as the power density was raised by 3 mW/cm^2 increments, indicated that a peak absorption rate of 29-34 W/kg and an average absorption rate of 8.4 W/kg were sufficient to produce a transient disruption in activity. This latter value is significant when the possible dependence of the microwave effect on wavelength is considered. The rat is a resonant structure for 918-MHz radiation; however, depression of the activity of rats was reported (*@MR0244*) to have occurred with 2.45-GHz radiation at an average SAR of 8 W/kg. Absorption by the structure responsible for radiation-induced behavioral modification was thus not frequency dependent; and the location or size of that structure was not subject to the geometric considerations usually applied to absorption of electromagnetic radiation. Nevertheless, thermal loading was concluded to be responsible for the behavioral changes observed.

In 1977, Mitchell et al (*@MR1991*) reported a significant alteration in innate and learned behavior patterns in rats during repeated irradiation with low-intensity microwaves. Fifteen female rats were separated into three groups for irradiation; 14 other females served as sham-irradiated controls. One group of five was subjected to operant reward conditioning for visual discrimination, and a second was trained under a Sidman avoidance regimen to respond to electric shocks. The final group of 5 and the 14 controls were observed for locomotor activity. After baseline performance levels had been established, the three groups were exposed to CW 2.45-GHz radiation at an average SAR of 2.3 mW/g. The animals were confined in individual polystyrene cylinders and placed together in a large multimode microwave resonant cavity. A total of 110 irradiations, each for 5 h/d, was performed during 22 weeks.

The temperature within the chamber was controlled, and measurements of rectal temperature taken during the irradiation procedure indicated that no increases occurred relative to those recorded under preirradiation conditions and in sham-irradiated controls (*@MR1991*). Locomotor activity of irradiated animals was almost twice that of controls, and discrimination ratios were increased to four times preirradiation levels. Changes indicative of hyperactivity and general irritability were evident during the 1st week of irradiation. Because there was no microwave-induced change in the avoidance reaction, the radiation effect was thought to be selective or specific to certain behavior patterns. Since heating did not occur, the rats' thermoregulatory mechanisms were able to compensate for the energy absorbed. The production of hot spots could not be ruled out; thus, proof of athermal microwave effects on behavior was not conclusive.

Microwave radiation, in contrast to electroconvulsive shock, anesthesia, brain stimulation, or changes of body temperature, was unable to produce retrograde amnesia in rats tested in a shock-avoidance learning task. Bryan (*@MR0484*) reported in 1966 that a pulse of 2.45-GHz microwaves sufficiently long and intense to raise the rectal temperatures of 80 male rats an average of 6 C lengthened the period before animals would descend from a platform in tests conducted 24 hours after radiation.

King et al (*@MR0871*), in 1971, showed that microwave radiation could serve as a reliable cue for suppressing operant behavior in rats. Six male rats were first trained to perform a tongue-licking routine; then a Pavlovian conditioning regimen was superimposed in which a cue was always presented prior to an electric shock. The result was a stable licking response that could be completely suppressed by the cue. The efficiencies of 1-minute-long sound and microwave radiation cues were compared while the rats were constrained in a Plexiglas conditioning chamber placed within a modified microwave oven. Doubly modulated (60 and 12 Hz) 2.45-GHz microwaves were used at average SAR's of 6.4, 4.8, 2.4, 1.2, and 0.5 mW/g. Over the 6-month testing period, 62 irradiation sessions were interspersed with 87 nonirradiation sessions, each 120 minutes long. The auditory cue was highly efficient in suppressing the operant response. Microwave radiation was less reliable, with the efficiency linearly related to the absorption rate. Temperature elevations were not observed, and the presence of artifactual cues was ruled out; thus, King et al concluded that rats could detect and learn to recognize microwave radiation.

Lambert et al (*@MR1180*), in 1972, reported negative effects of microwave radiation at high power densities on the behavior of beagles. Twelve male and 12 female dogs were trained to traverse a runway for a food reward on hearing an auditory cue. Performance was expressed as the time required to complete the run. Each dog was irradiated for 1 hour with CW 2.45-GHz microwaves at 88 and 176 mW/cm^2 and then tested. No significant differences in performance time were detected.

A 1971 study by Jankovich (*@MR0225*) showed that the performance rate of rhesus monkeys was decreased by microwave irradiation in direct proportion to the field intensity or exposure time. The operant-conditioned task was affected similarly by irradiation with 750- or 1,000-MHz microwaves under continuous or pulsed conditions. Power densities of 10 and 13 mW/cm^2 at 750 MHz and of 3 and 8 mW/cm^2 at 1,000 MHz were compared for exposure durations of between 10 and 95 minutes. The monkeys were trained, irradiated under far-field conditions with vertically polarized radiation, and tested in a Plexiglas test chamber located in an anechoic room. The general character of the effect was a decrease in the rate of performance, which immediately returned to normal when the electromagnetic field was switched off. At the lowest power density used (3 mW/cm^2), performance actually increased during short exposures of 20-30 minutes. Jankovich suggested that a more noticeable deterioration in performance could be expected with more complex psychologic tasks, although no supporting data were presented.

Rhesus monkeys, trained to perform a discriminatory lever-pressing routine in response to light stimuli, developed large deficits in performance when irradiated with 383-MHz microwaves, according to a 1975 report by Cunitz et al (*@MR1822*). Each monkey was trained to perform the behavioral task while suspended in a restraining chair, with its head protruding through the bottom plate of a cylindrical cavity resonator. The radiation series was initiated after 255 days or more of training, judged to be completed when errors were less than 2% of total responses during 5 successive days. The monkeys were irradiated for 5 days, 2 h/d, at six power levels. Two to 7 days were allowed between each 5-day exposure at each power level. Performance was measured daily during the irradiation series. The critical dose rate at which suppression of behavior was first noticed was 22.8±0.6 W/kg. Microscopic examination of sections of the brain of one monkey that failed to recover baseline performance after the final period of exposure revealed no changes. The dependence on critical dose levels, the delayed onset, and the reversibility of the effect suggested to Cunitz et al a neurochemical, rather than an electric or mechanical, mechanism for the action of microwave radiation. Serotonin was mentioned as possibly being involved because of its known action as a regulator of sleeplike states. Galloway and Waxler

(*@MR2946*) also implicated serotonin in the modification of behavior by microwave radiation.

Six male rhesus monkeys were used in behavioral experiments described by Galloway (*@MR0018*) in 1975. The monkeys were trained to respond to specific hue and line orientation stimuli and then were tested for discriminatory ability or repeated acquisition, ie, a sequence of four responses to four different stimuli. Irradiation with 2.45-GHz microwaves was observed to have no effect on performance except for the more complex repeated acquisition test after irradiation at 25 W. Galloway suggested that complex tasks were more sensitive to microwave irradiation than were simple tasks.

A 1976 report by de Lorge (*@MR2270*) showed that male rhesus monkeys trained to perform a vigilance task involving a double-lever response to two acoustic stimuli were unaffected by 30, 60, and 120 minutes of irradiation with 2.45-GHz microwaves at power densities between 16 and 62 mW/cm^2. Exposure at 72 mW/cm^2 affected the response rates in the three monkeys to various degrees. Increases in colonic temperature due to 60 minutes of irradiation were a logarithmic function of power density; however, experiments showed that thermal equilibrium could be obtained at each power density except 72 mW/cm^2.

Farrer et al (*@MR1950*) tested the performance of rhesus monkeys during microwave irradiation in 1976. Two monkeys were trained to maintain the horizontal attitude of a platform similar to an aircraft pilot's seat to within

±15° for both the pitch and roll axes. They were then irradiated with 3.2-GHz microwaves for 3 h/d on seven consecutive days. Performance was measured during three 45-minute sessions within each exposure period. The measured E-field strength at the surface of the monkey's head varied from 213 V/m at the nose to 736 V/m at the neck. Statistical analysis of the data indicated no decrement in performance when measurements made during irradiation were compared with those obtained during training.

Cardiovascular Effects

Cardiovascular changes reported after RF and/or microwave exposure have included changes in blood flow and pressure, changes in cardiac rate, and alterations in ECG readings. In addition, various studies have reported the induction of cardiac and circulatory disorders in populations exposed to relatively low levels of microwave radiation (*@MR1118,@MR0634,@MR0084,@MR0287,@MR1081,@MR0873,@MR0739*). These results are discussed in the section of this chapter dealing with epidemiologic studies. Table III-9 summarizes major animal studies involving cardiovascular effects produced after exposure to RF and microwave radiation.

Several early studies reported that microwave exposure could produce increased blood flow in the extremities. Wise (*@MR1482*), in 1948, reported measuring blood flow in the forearms of 10 men, aged 20-28 years, who were irradiated by a diathermy unit. A sensation of warmth in the arms as reported

TABLE III-9

CARDIOVASCULAR EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)	Duration	Remarks	Reference
Rat (6)	2.45	80 (far field?)	12 min (average)	Increased cardiac output, stroke volume, and cardiac work	Cooper et al (*@MR0550*)
Rat (30)	2.45	27.7, 40.1, and 68.2 cal/min (4.5-11.1 mW/g)	30 min	Bradycardia, some ECG abnormalities at higher doses	Phillips et al (*@MR1243*)
Rabbit (8)	2.4	7-12	20 min	Bradycardia or tachycardia, depending on area exposed	Presman and Levitina (*@MR1254*)
Rabbit (16)	2.4	10 (far field)	"	No significant changes	Kaplan et al (*@MR0919*)
Rabbit (2)	2.4	20-100 (far field)	"	Rise in cardiac rate at 100 only	"
"	2.4	20-80 (to head)	Two 1-h exposures	Small rise in heart rate at 40 and above	Birenbaum et al (*@MR0447*)
"	2.4	10 or 20 (to dorsum)	"	No significant change in heart rate	"
Rabbit (4)	2.8	20	Four 20-min exposures	No significant changes in heart rate; increased respiration and temperature	"
"	2.8 (PW)	20 (average)	"	"	"
Rabbit (8)	3.0 (PW)	3-5 (average)	20 min	Changes in cardiac rate (depending on area exposed)	Presman and Levitina (*@MR1747*)
Dog	2.45	20-100 (cranial exposure)	1 h	Changes in cardiac rate and contractility at 80 and 100	Lu et al (*@MR0114*)

by each patient was used to regulate dosage (further details not given). Except in one case, exposures were 10-20 minutes long. An increased blood flow in the forearm, as measured by a plethysmograph, was noted in all 10 men.

In 1951, Gloz (*@MR0786*) described the effects of microwave radiation of the head on blood vessel dilation. Details were not given on the extent or method of exposure. An increase in CSF pressure was observed in all subjects tested, and a decrease in systolic blood pressure was noted in 10 individuals. Control tests showed decreased CSF pressure and no blood pressure change. The author concluded that localized vasodilatation was produced by microwave exposure.

In a similar experiment, reported by Grynbaum et al (*@MR0934*) in 1950, several patients were found to have increased blood flow in their large toes after diathermy treatment. Abramson et al (*@MR0413,@MR0414*), in 1957 and 1960, found an increase in forearm blood flow after irradiation for 20 minutes at 27.12 MHz.

In 1960, Erdman (*@MR0666*) reported changes in blood flow to the legs of humans exposed to PW 27.12-MHz radiation (65 μs pulse width, 400-600 pps). Twenty persons (aged 25-38) were first monitored at rest until cardiac rate and temperature were at constant levels. A controlled-temperature room (22.8-23.9 C) was used for all testing. Maximum power output of the RF source was 1,025 W, with four intermediate levels used. Exposure occurred only during inhalation by the subjects, with the source 1 cm from the surface of the mid-upper abdomen. Subjects were not able to tell when irradiation took place. Plethysmographic recordings of blood flow to the leg revealed an increase in all 20 patients that was proportional to the intensity of irradiation. Although skin and foot temperatures increased, rectal temperatures and heart rates remained unchanged.

Obrosov et al (*@MR1897*), in 1963, described studies in which 10 individuals were irradiated at a frequency of 2.5 GHz directed to the cardiac region and 10 others were irradiated at the same frequency on the soles of their feet. A waveguide source (50-80 W) was positioned 7 cm from the exposed region. Irradiation time was 10 min/d for a total of five treatments (further dosage information not given). Slight changes were noted in respiratory rate, heart rate, atrioventricular conduction, and arterial blood pressure; however, no change persisted for more than about 4 hours, and the authors did not consider them harmful.

As discussed by Zaret (*@MR1707*), in 1976, an increased incidence of heart attacks has been reported in a region of Finland (North Karelia) that apparently lies in the path of a Soviet early-warning radar system. According to Zaret, the World Health Organization is studying this situation, but the increased incidence has not yet been explained. As noted by Puska (*@MR2976*), in 1973, and by the Finnish Institute of Radiation Protection (*@MR3116*), in a 1978 letter, the North Karelians have high levels of blood cholesterol and about 75% of the men smoke. In addition, hypertension appears to be common among the population. Furthermore, no unusually high microwave levels exist in the region in question (*@MR3116*). Therefore, any correlation between exposure to microwave radiation and heart attacks in this region of Finland is speculative.

Cooper et al (*@MR0550*), in 1962, described experiments in which six male albino rats, each weighing 0.4-0.5 kg, were exposed to 2.45-GHz radiation at 80 mW/cm^2. A microwave generator was placed 5 cm from the upper abdomen. Twelve minutes of exposure was the average time required to elevate the rectal temperature to 40.5 C, at which point the radiation was stopped. Six cardiac variables were measured prior to irradiation and again after 40.5 C was reached. Cardiac output and stroke volume increased by 40-50%; cardiac work increased by more than 50%. Heart rate and mean arterial blood pressure increased slightly. Peripheral resistance fell by approximately 30%. The changes in cardiac output, stroke volume, and cardiac work were statistically significant. Cooper et al (*@MR0184,@MR0561*) obtained similar results in additional studies performed in 1962 and 1965.

Presman and Levitina (*@MR1254*), as reported in 1962, exposed various parts of eight male rabbits to 2.4-GHz microwave radiation at 7 and at 12 mW/cm^2. Dorsal and ventral aspects of the animals were irradiated separately for 20 minutes by means of a 40- x 40-cm horn antenna. Electrocardiogram recordings were made before, during, and after irradiation.

Another group of rabbits served as controls. All rabbits ventrally exposed developed a bradycardia that did not disappear promptly after the irradiation ceased. Rabbits exposed dorsally generally had no significant change in cardiac rate. An increase in heart rate occurred during irradiation of the back of the head, with the greatest change occurring after termination of exposure. Although each rabbit underwent repeated periods of irradiation, no cumulative effects due to radiation were observed. The authors concluded that the effects seen were indicative of a nonthermogenic microwave effect. In a further study, Presman and Levitina (*@MR1747*) used pulsed microwave radiation (700 pps, pulse duration of 1 μs, at a frequency of 3.0 GHz, and at an average power density of 3-5 mW/cm^2), and the results, as reported in 1962, were similar. Dorsal irradiation of the head with pulsed microwave radiation caused a greater increase in heart rate than that with CW radiation.

In a 1964 report, Levitina (*@MR2124*) described the results of experiments in which rabbits were exposed at much higher power density levels. Animals were irradiated with either pulsed 3-GHz radiation (1 μs pulse width, 700 pps, 2 series per second, series duration of 0.1 second, mean power density 350-385 mW/cm^2) or "continuous pulsed" 2.4-GHz radiation with a "mean pulse intensity" of 740-1,250 mW/cm^2 (2 pps, pulse duration = 0.1 second). Several different areas of the rabbits were exposed for single exposure periods of 20 minutes. Electrocardiogram recordings showed that disturbances in cardiac rhythm could be produced in varying numbers of animals depending on the location of irradiation. The study was not designed to detect any dose-effect relationship.

Kaplan et al (*@MR0919*), in 1971, attempted to duplicate the studies of Presman and Levitina (*@MR1254*). A 20- x 15-cm horn antenna was used to irradiate 16 male rabbits in an anechoic chamber with 2.41-GHz radiation. The back of each animal's head was exposed in the far field at 10 mW/cm^2. Evaluation of ECG records indicated that no significant changes in rhythm were produced. In additional experiments, the authors found that a 20-minute exposure to 100 mW/cm^2 directed at the backs of the heads of two rabbits produced a consistent increase in heart rate. Irradiation at lower power densities had no effect on heart rate but did increase body temperature and respiratory rate.

A 1975 report by Phillips et al (*@MR1243*) appears to be consistent with reports of bradycardia induced after microwave exposure. Rats were exposed in a cavity to 2.45-GHz radiation, and doses were reported in terms of calories per minute. The authors estimated that the plane-wave equivalent power density necessary to produce the slowed heart rates would be about 31 mW/cm^2.

In 1975, Birenbaum et al (*@MR0447*) reported the results of three experiments in which two male rabbits were exposed to microwave radiation at varying power densities. Heart rate, respiration, and subcutaneous temperature were recorded. Each animal was placed in an open box, restrained, and allowed

10 minutes for acclimatization before receiving far-field radiation from a 20-x 15-cm rectangular horn. Three procedures were scheduled 1 week apart. In the first experiment, the dorsal regions of the heads of the two rabbits were exposed twice to CW 2.4-GHz radiation at power levels of 0-80 mW/cm^2 for 1 hour. Increases in heart rate, respiratory rate, and subcutaneous temperature were produced that were related to power density. In a second procedure, four rabbits received CW and PW (1,000 pps, pulse width 1.3 μs) radiation at 2.8 GHz over their entire dorsal surfaces. Each animal received four 20-minute doses of CW radiation and four 20-minute doses of PW radiation, all at 20 mW/cm^2. No change in heart rate was produced, but respiratory rate and temperature were increased. No significant differences in effect were noted between CW and PW radiation. In the third experiment, the entire dorsal surface was exposed to 2.4-GHz radiation at 10 and 20 mW/cm^2. Each animal was exposed twice, with each exposure lasting 1 hour. The increase in respiratory rate far exceeded the insignificant rise in heart rate, which was related to the rise in temperature.

In a 1961 report, Marks et al (*@MR1072*) published the results of an experiment in which 12 dogs were irradiated by a diathermy generator placed 2.5, 3.8, or 5 cm from the chest wall. The animals were anesthetized and exposed to 2.4-2.5 GHz microwaves for 15-140 minutes. Throughout the procedure, a power level of 125 W was used. Heart rate rose by 15-30%. Alterations in ECG readings, specifically, changes in the T-wave, were observed. Microscopic examination of the mediastinum revealed injury similar to thermal injury in that area. Specific cardiac effects included engorgement of the coronary arteries and intramyocardial arterioles. In a subsequent study, Marks et al (*@MR1073*) failed to find any changes in cardiac output, mean blood pressure, and peripheral resistance as a result of exposure to microwaves. The activities of several enzymes in the blood that might reflect cardiac damage were measured, but no changes were noted.

In 1974, Lu et al (*@MR0114*) reported on cardiovascular changes in anesthetized dogs exposed to microwave radiation. The dorsal cranial area was exposed to 2.45-GHz radiation for 1 hour at power densities from 20 to greater than 100 mW/cm^2. A power density greater than 50 mW/cm^2 was necessary to produce an elevation in temperature. Increased heart rate was produced after exposure at 80 mW/cm^2. Pulmonary blood flow and systemic blood pressure were not affected by irradiation. Changes in body temperature were correlated with the changes noted in cardiac rate and contractility. Corrections for the effects of anesthesia were made in an unspecified manner. The authors concluded that the effects seen were induced by thermal effects of microwave exposure.

Hematologic Effects

Hematologic effects reported in humans after exposure to RF and microwave radiation have included changes in WBC count (*@MR0856,@MR0857,@MR0739,

@MR1405,@MR2667*), red blood cell (RBC) count (*@MR0856,@MR0857*), and platelet counts (*@MR0850,@MR2667*). However, one report noted a lack of hematologic changes in exposed individuals (*@MR0170*). Since these studies involved relatively large numbers of subjects, they are discussed in detail in Epidemiologic Studies.

Table III-10 summarizes major studies that have described hematologic effects in animals exposed to RF and microwave radiation.

Spalding et al (*@MR2826*) reported in 1971 that mice exposed to 800-MHz radiation 2 h/d, 5 d/wk for 35 weeks exhibited no significant changes in peripheral blood variables. Animals were exposed in a waveguide at a reported average incident power density of 43 mW/cm^2.

In 1972, Rotkovska and Vacek (*@MR1287*) described experiments in which they exposed female mice to 2.45-GHz radiation at 100 mW/cm^2 for 5 minutes. Effects on the hematopoietic system were determined by measuring ^{59}Fe incorporation into spleen and bone marrow cells. Incorporation into the spleen showed a gradual increase to a statistically significant level at 14 days postexposure, whereas incorporation into the bone marrow did not differ from that in controls. The number of hematopoietic stem cells in the spleen showed a significant increase 48-72 hours after exposure.

TABLE III-10

HEMATOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse (24)	0.8	43	2 h/d, 5 d/wk for 35 wk	No changes in blood composition--RBC and WBC counts, hematocrit, or hemoglobin	Spalding et al (*@MR2826*)
Mouse	2.45	100 (whole body)	5 min	Increase in splenic iron uptake	Rotkovska and Vacek (*@MR1287*)
"	2.45	100 (whole body) (controlled temperature)	"	Increase in WBC count and blood-forming cells	Rotkovska and Vacek (*@MR0285*)
Mouse (54)	2.95 (PW)	0.5±0.2 (far field)	4 h	Increase in mitotic indices in stem cells	Czerski et al (*@MR1605*)
Mouse (groups of 90)	9.37	17-60 mW/cm^2	Approx 4-13 min (single or multiple exposures)	No significant changes in hemoglobin and WBC count	Hyde and Friedman (*@MR0093*)
Rat (115)	0.006 and 0.014	2,000 V/m, 5 A/m or more	--	Decreased WBC count followed by slow recovery	Henny et al (*@MR1229*)
Rat (14)	0.4	100 (waveguide)	30 min, 3 x wk for 4 wk	Decrease in WBC count	Lubin et al (*@MR1220*)
Rat (30--estimate)	2.38	0.01, 0.05, and 0.5	7 h/d for 30 d	Changes in glycogen content and alkaline phosphatase activity in neutrophils	Gonchar (*@MR3046*)
Rat (10)	2.4	10	2 h/d for 10, 20, and 30 d	Increase in RBC and WBC counts	Djordjevic and Kolak (*@MR0016*)
Rat (30)	2.4	5	1 h/d for 90 d	No significant changes	Djordjevic et al (*@MR0122*)
Rat	2.4	0.05	6-h exposures for 3, 7, or 10 d	Changes in morphology and function of bone-marrow megakaryocytes	Obukhan (*@MR1600*)
"	2.4	0.5	Single 6-h exposure	Same as above but more pronounced	"

TABLE III-10 (CONTINUED)

HEMATOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat (6)	2.45	10	16 h	No changes in hematocrit, leukocyte, lymphocyte, and eosinophil counts	Parker (*@MR0038*)
Rat (pregnant) (groups of 6)	2.45	5 or 25	10 or 20 min/d for 15 d	Dose-dependent increase in iron-binding capacity	Travers and Vetter (*@MR1459*)
Rat	3	1 or 10	1 h/d for 6-9 mo	Decrease in RBC count (at 1 mW/sq cm) and lymphocytes	Sokolova (*@MR2661*)
Rat	24	20	7 min-7.5 h	Strain-dependent changes in hemoglobin, hematocrit, RBC count, leukocytes, lymphocytes	Deichmann et al (*@MR0193*)
"	24	10	3 h	"	"
Rat	37.5-60	1	15 min/d for 60 d	Decrease in RBC count and hemoglobin content and shifts in WBC count (however, data not given)	Zalyubovskaya (*@MR0749*)
Guinea pig (100)	3 (CW and PW)	3.5 (average)	3 h/d, 6 d/wk for 3 mo	Increase in WBC count, cytologic changes in erythroblasts and lymphoblasts	Baranski (*@MR0169*)
Rabbit (100)	"	"	"	Increase in WBC count	"
Rabbit (4)	2.45	7 (body axis) 10 (head)	23 h/d for 6 mo	No significant differences in hematocrit, hemoglobin, WBC count, platelet count	Guy et al (*@MR0349*)
Rabbit (6)	2.45	10 (±3)	8 h/d, 5 d/wk for 8-17 wk	Alterations in RBC count	Ferri and Hagan (*@MR2093*)

TABLE III-10 (CONTINUED)

HEMATOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rabbit (50)	2.95 (PW and CW)	3 (far field)	2 h/d for 74 or 158 h	Decrease in iron transport and turnover rate and in RBC production	Czerski et al (*@MR1823*)
Dog (4)	0.2	165	6 h	Variable change in leukocytes, neutrophils, lymphocytes, and eosinophils	Michaelson et al (*@MR0257*)
Rat (20)	2.74 (PW)	24.4	4 h/d, 5 d/wk for 7 wk	Significant decreases in hematocrit, leukocyte, and lymphocyte count	Pazderova-Vejlupkova and Josifko (*@MR3108*)
Dog	1.29 (PW)	20, 50, and 100	6 h/d, 5 d/wk for 4 wk	Increase in hematocrit after 100, decrease after 20 and 50 mW/cm^2, reticulocytosis	Michaelson et al (*@MR0252*)
Dog (11)	1.29 (PW)	100	6 h	Fluctuation in WBC count, lymphocytosis	"
Dog (21)	24 (PW)	50	6 h/d for 5 d	Decrease in reticulocytes, lymphocytes, hemoglobin, and hematocrit	Michaelson et al (*@MR1090*)
Dog (9+)	1.28 (CW and PW)	20-100	6 h/d, 5 d/wk for 2-4 wk	Variable changes in lymphocytes and neutrophils	Michaelson et al (*@MR0254*)
Dog (11)	1.29	100	6 h	Variable change in leukocytes, lymphocytes, neutrophils, and eosinophils	Michaelson et al (*@MR0257*)
Dog (9)	2.8	100	"	"	"
Dog (11)	2.8	165	2 h	"	"
Dog (8)	2.8	165	3 h	"	"

TABLE III-10 (CONTINUED)

HEMATOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Dog (9)	2.8	100	5.5-6 h	Changes in lymphocytes, eosinophils, and neutrophils	Michaelson et al (*@MR0258*), Michaelson (*@MR0251*)
Dog (19)	2.8	165	1.5-3 h	"	"
Dog (9)	2.8 (PW)	100	6 h	Transient (1 d) decrease in lymphocytes and increase in neutrophils	Thomson et al (*@MR1451*)
Dog (2)	24 (PW)	24	6.67 and 16.5 h/d for 20 mo	No significant differences in hematocrit, hemoglobin, erythrocytes, and leukocytes	Michaelson et al (*@MR0254*)
Monkey (8)	0.015 and 0.02	760-1,270	Four 3-h exposures	No significant alterations in packed cell volume, WBC count, or hemoglobin when compared with normal values	Krupp (*@MR1565,@MR1566*)
Monkey (10)	0.026	500-1,000	Two 6-h exposures	"	Krupp (*@MR1566*)

*Unless otherwise specified

In a related study, Rotkovska and Vacek (*@MR0285*), in 1975, compared the hematopoietic effects of exposure to microwaves and to heat. The rectal temperature of mice exposed to 2.45-GHz radiation at 100 mW/cm^2 increased by a mean of 2.3 C. Mice exposed to heat showed an average increase in rectal temperature of 2.5 C. Both procedures produced an increase in ^{59}Fe incorporation, but the time courses were different. Similar results were obtained regarding the number of hematopoietic spleen cells. In general, exposure to microwaves was more effective than was heat in stimulating hematopoiesis. The authors concluded that the effects of microwaves might not be related solely to thermal changes.

Czerski et al (*@MR1605*), in 1974, reported exposing two groups of 54 inbred 20-g Swiss albino mice to 2.95-GHz microwaves (PW, 1,200 pps, pulse width 1 μs) at 0.5±0.2 mW/cm^2 vertical polarization, far field. The authors stressed that power density was measured in the absence of the animals and that absorbed doses were sufficiently low that rectal temperature was unaffected. Sham-irradiated controls were used with each group. Beginning at 28 hours after exposure, three experimental mice were killed every 4 hours for 72 hours. Bone marrow smears were prepared, and mitotic indices were plotted against time. On day 2, the mitotic indices of stem cells (undifferentiated and lymphocytelike cells) were more than twice those of controls, with a loss of the diurnal cycle in both experimental groups. No significant differences in the mitotic indices of granulocyte precursors and erythroblasts were noted between irradiated mice and controls. The authors concluded that exposure to microwaves might interfere with the circadian rhythm of certain body cells.

In 1968, Hyde and Friedman (*@MR0093*) described the exposure of anesthetized female mice to PW 9.37-GHz microwave radiation. Preliminary studies indicated that exposure at 0.22 Wmin/cm^2 (approximately 17-60 mW/cm^2 for 4-13 minutes) produced an "intraperitoneal" temperature of 40 C. Groups of 90 mice were exposed at 0.22 Wmin/cm^2 under three conditions: (1) a complete single dose, (2) continuous irradiation until "intraperitoneal" temperature was 40 C, and (3) intermittent radiation such that "intraperitoneal" temperature did not exceed 37.4 C. The hemoglobin concentrations in the blood were measured, and WBC counts were made up to 20 days after exposure. Although no significant differences were found between the irradiated groups and the controls, the authors noted that irradiated animals tended to have leukopenia followed by a rebound leukocytosis.

In a study using 115 rats, Henny et al (*@MR1229*), in 1970, found that animals irradiated with 6- and 14-MHz radiation showed large decreases in WBC counts 1 day after irradiation. White blood cell counts then rose steadily until, after about 30 days, they once again reached the preirradiation control level. Little effect was noted on RBC count, hemoglobin concentration, or platelet count. Thin sections from various biologic tissues showed evidence of pathologic damage that seemed to be greater at 14 MHz than at 6 MHz. Unfortunately, these results are difficult to interpret, since little specific dose information was given. Animals were apparently exposed to H-field strengths of 5 A/m or greater, E-field strengths of 200 V/m or greater, or both. No attempt was made, however, to specifically link dose and effect.

Lubin et al (*@MR1220*), in 1960, exposed 14 male Wistar rats in a waveguide to 400-MHz radiation at 100 mW/cm^2 for 30 minutes, three times/wk for 4 weeks. Average rectal temperature increased by 3.5±0.2 C during exposure. The experimental group had a significant decrease in leukocyte count (average 17,000±2,500) compared with that for controls (24,000±1,400) measured within 2 weeks after the last exposure.

Djordjevic and Kolak (*@MR0016*) subjected groups of 10 male Wistar rats to 2.4-GHz radiation at 10 mW/cm^2, 2 h/d for 10, 20, or 30 days, as described in a 1973 report. Animals were exposed in cages and were free to move. Rectal temperature rose 1 C during exposure. Erythrocyte count, hematocrit, and hemoglobin concentration increased in proportion to the length of exposure. White blood cell counts in most of the animals increased during 20 days of exposure; with the longer exposure, the counts returned to baseline levels. The eosinophil counts followed the reverse course. The authors concluded that the changes seen were consistent with physiologic adaptation to a thermal stress. In a subsequent study, Djordjevic et al (*@MR0122*), in 1977, reported that exposure of rats to 2.4-GHz radiation at 5 mW/cm^2 for 1 h/d for 90 days produced neither a change in rectal temperature nor alterations in hematologic parameters. These findings were taken to support the adaptation hypothesis.

Microwave radiation-induced changes in bone marrow megakaryocytes were observed in experiments reported in 1977 by Obukhan (*@MR1600*). Rats were exposed to 2.4-GHz radiation at two dose levels. Animals in one group received a single 6-hour exposure at 500 $\mu W/cm^2$, and animals in a second group were exposed for 6 h/session at 50 $\mu W/cm^2$ for 3, 7, or 10 days. Bone marrow smears were made at various times after irradiation. Observations included destruction of some megakaryocytes and increased megakaryophagocytosis, thrombocytopoiesis, and proliferative capacities of megakaryoblasts and promegakaryocytes compared with controls. The greatest effects were seen in animals irradiated with the single dose. Information was lacking in this report on dosimetry and on the exact number of animals used.

Parker (*@MR0038*), as reported in 1973, exposed rats to CW 2.45-GHz microwaves at a distance of 170 cm. Rectal temperatures were measured 5 minutes after sham or microwave irradiation. Exposure at 10 mW/cm^2 for 16 hours led to an increase of only 0.4 C. No significant differences were found between irradiated and sham-irradiated groups with respect to hematocrit and total leukocyte, lymphocyte, and eosinophil counts. Further details of this study can be found in <u>Effects on the Neuroendocrine System</u>.

Valtonen (*@MR2553*), in 1966, reported exposing white rats at 2.43 GHz to a power level of 80 W directly beneath a 17-cm-diameter director for 5 minutes. Differential counts of the WBC's done 3 and 20 hours after exposure revealed no significant changes compared with those of matched controls. No further dosage information was given.

In 1975, Travers and Vetter (*@MR1459*) studied the effects of irradiation with low-level microwaves on the total iron-binding capacity of pregnant rats. Groups of six rats were exposed in plastic restraining cages on days 6 through 21 of pregnancy to 2.45-GHz microwave radiation at 0, 5, or 25 mW/cm^2 for 10 or 20 minutes. Blood samples were taken for analysis before irradiation on day 5 of pregnancy and following the exposure periods on days 10, 15, and 20. The total iron-binding capacity plotted against time for the 10-minute exposures at 0 mW/cm^2 and at 5 mW/cm^2 revealed a decrease on the 5th day of exposure followed by a sharp increase to the 15th day. After the exposures at 25 mW/cm^2, iron-binding capacity steadily increased to the 15th day of exposure. This capacity underwent the same pattern of changes during the series of 20-minute exposures. Statistically significant differences in the total iron-binding capacity were observed among the two power densities (5 mW/cm^2 and 25 mW/cm^2) and the controls, among the four different sampling days, and between 10- and 20-minute exposure periods. The results suggested a microwave radiation-induced increase in the synthesis of transferrin, the protein responsible for binding and transporting iron.

In a study of combined effects of electromagnetic fields and X-rays, Sokolova (*@MR2661*) reported results in which rats were exposed to microwaves alone. Animals were subjected to 3-GHz microwaves at 10 mW/cm^2 and 1 mW/cm^2, 1 h/d for 6-9 months. The mean WBC count for the group exposed at 10 mW/cm^2 decreased to below that for the controls for 2 months, rebounded to above the control level until 3.5 months, and then remained below the control level for the next 9 months. For the group exposed at 1 mW/cm^2, an initial increase in the WBC count was noted for 2.5-3.5 months and was followed by a decrease in the WBC count that persisted for 7 months. Both decreases in WBC counts were due to decreases in the concentration of lymphocytes in the blood. Red blood cell concentrations in the blood of animals exposed at 1 mW/cm^2 decreased significantly from control levels after 2.5-4.5 months and remained depressed for 7 months.

Changes in the blood after microwave irradiation were noted in a 1979 report by Pazderova-Vejlupkova and Josifko (*@MR3108*). A group of 20 rats was irradiated for 4 h/d, 5 d/wk, for 7 weeks with 2.74-GHz pulsed-wave radiation (395 pps, 2.6-μs pulse width). The mean power density was 24.4 mW/cm^2 (±6%), and polarization was vertical. The maximum increase in rectal temperature was 0.5 C. Blood was taken at various intervals before, during, and after the irradiation period. Irradiated animals had significant decreases in hematocrit values and in leukocyte and lymphocyte counts in comparison with controls. These differences gradually disappeared several weeks after the end of the irradiation period. Transient changes in alkaline phosphatase activity were detected in neutrophilic leukocytes at the beginning and at the end of the irradiation period.

Gonchar (*@MR3046*), in 1978, noted effects of microwave irradiation on cytochemical indices of leukocytes. Rats were exposed to 2.38-GHz radiation at either 0.01, 0.05, or 0.5 mW/cm^2 for 7 h/d for 30 days. Increases were observed in the glycogen content of neutrophils of animals exposed at 0.01 and 0.05 mW/cm^2. Neutrophils from rats exposed at 0.5 mW/cm^2 exhibited a decreased glycogen content, indicating to the authors that different mechanisms of action may have been responsible for the changes observed. At all incident dose levels, the alkaline phosphatase activity of the neutrophils was found to increase during the first 3 weeks of irradiation and to decrease subsequently. The authors concluded that the observed changes were indicative of microwave radiation-induced stress to the energy metabolism of the neutrophils.

In 1977, Zalyubovskaya (*@MR0749*) reported alterations in erythrocyte and leukocyte counts after exposure of rats to "radio waves in the 5-8 millimeter range" (37.5-60 GHz) at a reported 1 mW/cm^2 for 15 min/d for 60 days. Numerous other effects were also noted. However, since the paper failed to present any specific data, the significance of the reported results cannot be evaluated.

Deichmann et al (*@MR0193*), in 1964, exposed three strains of rats to 24-GHz radiation. Osborne-Mendel rats were continuously exposed at 20 mW/cm^2 for 7.5 hours in one experiment and at 10 mW/cm^2, 3 hours every 2nd day, for six exposures in a second experiment. A 10-minute exposure at 20 mW/cm^2 was given to CFN rats. Fischer rats received a 3-hour exposure at 10 mW/cm^2. All exposure conditions produced, in all strains, a moderate decrease in the total leukocyte count and a decrease in the proportion of lymphocytes. Recovery occurred in 3-7 days and was related to power density. A tendency toward increased RBC counts and hemoglobin concentrations was shown by Osborne-Mendel and CFN strains, whereas Fischer rats showed decreases.

Baranski (*@MR0169*), in 1971, exposed 100 guinea pigs and 100 rabbits to either CW or PW radiation (3 GHz) at 3.5 mW/cm^2. All animals were exposed 3 h/d, 6 d/wk, for 3 months. Fifty animals of each species served as controls. Determinations of RBC, WBC, and differential counts were made before the exposure period and for up to 4 weeks afterward. Mitotic indices were determined for bone marrow, spleen, and lymph nodes immediately after exposure.

Continuous-wave and pulsed radiation produced similar effects in both species (*@MR0169*). No increases in rectal temperature greater than 0.5 C were noted immediately after irradiation. In guinea pigs, the total WBC count increased by 51-56%, and lymphocytes increased to levels 2.0- to 2.2-fold greater than their baseline values. The lymphocytosis reached a peak during the first 2 weeks after exposure ended and then gradually returned toward the baseline value. The effects in rabbits reportedly were similar. Significant decreases were found in the mitotic index for the erythroblastic system of guinea pigs. Exposure of 10 guinea pigs for 4 months produced an even greater decrease in the mitotic index. This parameter aproached the baseline value approximately 1 month after the end of CW exposure, whereas, after PW irradiation, hypercompensation was seen. The author proposed that lymphocytosis might be useful as an indicator of human overexposure to microwaves.

Guy et al (*@MR0349*), in 1976, described the complete absence of biologic effects in rabbits after chronic low-level microwave irradiation. Four exposed rabbits were placed in a temperature-controlled anechoic chamber with the E-field vector polarized parallel to the long axis of the cage. Animals were exposed to CW 2.45-GHz radiation for 23 h/d for 6 months at an effective power density of 7 mW/cm^2 at the body axis and of 10 mW/cm^2 at the head. The peak SAR for the head was calculated to be 14 W/kg. Periodic examination of the eyes and monitoring of body weight, urinary output, rectal temperature, hematocrit, hemoglobin, differential count, WBC count, platelet count, and blood coagulation indicated no significant differences between microwave- and sham-irradiated animals.

Ferri and Hagan (*@MR2093*), in 1976, described changes in the blood of rabbits after long-term exposure to 2.45-GHz radiation. Six unanesthetized rabbits were exposed in an anechoic chamber at an incident power density of 10 (±3) mW/cm^2 for 8 h/d, 5 consecutive days per week, for 8-17 weeks. Weekly blood counts were made, and the results were compared with data from control animals. A comparison of the mean RBC counts indicated significant alterations in the irradiated animals; however, pretreatment counts were not given. No definite trends were observed with cumulative exposure. Analysis of mean WBC counts showed no significant difference between control and exposed animals.

Czerski et al (*@MR1823*) studied the effect of microwave exposure on ^{59}Fe transport and turnover. Three groups of rabbits were exposed to 2.95-GHz PW (1,200 pps, 1-μs) or CW radiation at 3 mW/cm^2, 2 h/d for a total of 74 or 158 hours. Animals were positioned with the head directed toward a horn antenna in the far-field zone. Measurements of the concentration of iron in the blood, using ^{59}Fe, revealed decreased iron transport and turnover rate, quantity of iron incorporated into RBC's, and red cell production 100 minutes after the end of the irradiation period. Exposure to PW radiation for 74 hours induced more pronounced effects than exposure to CW radiation for the same length of time, and these effects resembled those produced by exposure to CW radiation for 158 hours.

In 1970, Yagi (*@MR1506*) described studies of localized high-level microwave exposure (2.5 GHz at power levels of 50-200 W) to the thigh of the rabbit. Irradiation for 30 minutes was performed five times daily for 7 days. The localized temperature of the leg rose to 42-43 C during exposure. Counts of circulating WBC's revealed a marked increase during the exposure period and a return to normal by 2 weeks postexposure. Differential WBC counts revealed that this increase was due to increases in the numbers of neutrocytes and large lymphocytes. Localized tissue injury resulted in completely aplastic bone marrow by the 5th to the 6th week after exposure ended.

Changes in blood components produced by exposure of dogs to microwaves were reported in 1965 by Michaelson et al (*@MR0252*). Animals were exposed to PW 1.29- and 2.8-GHz radiation (pulsing parameters not specified) at average power densities of 20-100 mW/cm^2 for 6 h/d. Measurements were made of hematocrit and differential leukocyte count during exposure and up to 12 months following exposure. Acute exposure to both frequencies tended to increase the relative number of neutrophils and to decrease those of lymphocytes and eosinophils. Variable changes in hematocrit were noted. Abnormalities in differential leukocyte counts persisted for up to 12 months. Chronic exposure of dogs to 1.29-GHz radiation 6 h/d, 5 d/wk, for 4 weeks resulted in decreased counts of neutrophils and reticulocytes and decreased (50 and 100 mW/cm^2), or increased (20 mW/cm^2), counts of lymphocytes. Changes were most marked after exposure at 100 mW/cm^2, but subtle effects were noted at 20 mW/cm^2. Rectal temperature increased during exposures at 50 and 100 mW/cm^2.

In a related 1967 study, Michaelson et al (*@MR1090*) exposed dogs to PW 1.24-GHz radiation (360 pps, 2 μs pulse width) at 50 mW/cm^2, 6 h/d for 5 days. After repeated exposures, reticulocyte and lymphocyte counts decreased by 67 and 16%, respectively. Hematocrit and concentration of hemoglobin also declined. However, the WBC, neutrophil, and RBC counts and the erythrocyte sedimentation rate remained unchanged. Further details of this paper are given in <u>General Physiologic and Other Effects</u>.

The response of leukocyte counts in adult dogs exposed to PW 2.8-GHz radiation (360 pps, 2-μs pulse width) was described by Thomson et al (*@MR1451*) in 1966. Dogs were restrained in a Plexiglas cage within an anechoic chamber for 6 hours. Irradiation at 100 mW/cm^2 led to an immediate 29.5% increase in the concentration of neutrophils and a 59.8% decrease in lymphocytes. Within 1 day after irradiation, the lymphocyte count had returned to near-normal levels, the neutrophil count had increased slightly, and the total WBC count had increased by 22.8%. The concentrations of these cells declined thereafter to 68.5, 66, and 67.4%, respectively, of the preexposure levels. Rectal temperature rose by only 1 C following irradiation. Comparative studies of the combined action of microwave and X-irradiation revealed an additive effect and suggested that bone marrow changes occur in response to exposure to either type of radiation.

Results of an examination of the hematologic effects of microwave irradiation on 43 dogs were described by Michaelson et al (*@MR0257*) in 1964. During irradiation, each dog was confined in a Plexiglas cage within an anechoic chamber. Two hours of irradiation with PW 2.8-GHz radiation (pulsing parameters not specified) at 165 mW/cm^2 (condition 1) produced a 21% decrease in the concentration of leukocytes 1 minute after irradiation; after 24 hours, the decrease was only 13.5%. Corresponding lymphopenia, neutropenia, and eosinopenia were evident. In contrast, the following exposures produced increases in the concentrations of leukocytes and of neutrophils at both 1 minute and 24 hours after irradiation: 2.8 GHz (PW) at 165 mW/cm^2 for

3 hours (condition 2); 2.8 GHz at 100 mW/cm^2 for 6 hours (condition 3); 1.28 GHz (PW) at 100 mW/cm^2 for 6 hours (condition 4); and 200 MHz (CW) at 165 mW/cm^2 for 6 hours (condition 5). All five of these exposure conditions produced an initial decrease in lymphocytes. Eosinophils decreased after all irradiations except condition 2. By 24 hours after the end of irradiation, lymphocytes and eosinophils had returned approximately to initial levels for all irradiations except condition 2. During the exposures, the mean increase in rectal temperature was 1 C.

The effects on leukocyte counts of 6 hours of PW 2.8-GHz irradiation at 100 mW/cm^2 also was monitored weekly for 60 days and monthly for 6 months (*@MR0257*). The WBC count diminished to the preexposure level by 5 days after the cessation of irradiation and within 16 days following PW 1.29-GHz irradiation. A further decrease occurred during the 60 days after the end of the exposure, but a decrease was followed by recovery to 97% of the initial count after the latter. The concentrations of neutrophils followed a quantitatively similar course. The initial decreases in lymphocyte counts (40% with 2.8-GHz and 49% with 1.29-GHz radiation) and eosinophil counts (33 and 38%, respectively) were followed by recovery at 24 hours and subsequent decreases during the 60-day period. Eosinophils maintained their 24-hour counts over the 60 days. Monthly counts after 1.29-GHz irradiation indicated that the concentration of eosinophils gradually increased, that of lymphocytes increased by the 1st month and then remained stable, and that of neutrophils decreased at 3 months but then returned to near-normal levels by 6 months.

In a discussion of these observations, Michaelson et al (*@MR0257*) attributed the sustained eosinopenia and transient lymphocytopenia and neutrophilia to increased adrenal function resulting from thermal stimulation of the hypothalamic-adrenal complex. This secondary leukocytic action was accompanied by a direct effect of microwave irradiation on the bone marrow.

Observations on the physiologic aspects of microwave irradiation of dogs were made by Michaelson et al (*@MR0258*) in 1961 and by Michaelson (*@MR0251*) in 1970 (see <u>General Physiologic and Other Effects</u> for further details). Young adult animals, constrained by a Plexiglas holder in an anechoic chamber, were irradiated with PW 2.8-GHz microwaves (2-3 μs pulse width, 360 pps). Weakness, followed by collapse, occurred within 4-6 hours at 100 mW/cm^2 or within 2-3 hours at 165 mW/cm^2 (*@MR0251*). During irradiation at 165 mW/cm^2, rectal temperatures increased initially by 1-2 C, stabilized for 40 minutes, and then increased another 2-3 C. Irradiation with 100 mW/cm^2 produced some initial heating but no ultimate rise in temperature. After 4.5 hours of irradiation, body weight had decreased 6% at 100 mW/cm^2 and 8.5% at 165 mW/cm^2. Hematocrit values increased at the same time, indicating dehydration, and disparate effects on WBC's were noted. These consisted of decreases in lymphocytes and eosinophils and increases in neutrophils.

In a long-term study of the effects of chronic microwave exposure on dogs, Michaelson et al (*@MR0254*), in 1971, noted a number of frequency-dependent variables but no permanent physiologic changes. Two dogs were irradiated with

PW 24-GHz microwaves (duty cycle 6×10^{-5}, other pulsing parameters not specified) at 24 mW/cm^2 for 20 months. One dog was exposed for 6.67 h/d for 5 d/wk, and the other was exposed for 16.5 hours on each of 4 d/wk. Irradiation of nine dogs with PW 1.285-GHz microwaves (3-μs pulse width, 360 pps) at 20, 50, or 100 mW/cm^2 was performed for either a total of 6 hours or for 6 h/d, 5 d/wk, for 2-4 weeks.

Irradiation with 24-GHz microwaves produced a 16% loss of blood volume but no differences in hematocrit, hemoglobin, count of erythrocytes, and total and differential leukocyte counts (*@MR0254*). At 1.28 GHz, however, neutrophils increased by 100% after 100 mW/cm^2 (fourth exposure), and lymphocytes decreased by 75% (first exposure). Irradiation at 50 mW/cm^2 produced smaller changes. The magnitude of the microwave-induced changes decreased during the 2nd week. The authors considered the observed effects to be transitory and not significant when irradiated animals were compared with matched controls.

The capability of rhesus monkeys to compensate for the thermal load induced by microwave irradiation was described by Krupp (*@MR1565*) in 1977. Ten animals were placed, one at a time, in a plastic cage above a coaxial transmission line so that the animals' long axis and the E-vector were vertical. Rectal temperatures rose rapidly during the first 30 minutes of exposure to CW high-frequency radiation and then leveled off for the remaining 2 hours of the experiment. The average maximum rise induced was 1.60 C for 20-MHz radiation at 1.27 W/cm^2; 0.92 C for 20-MHz at 0.76 W/cm^2; 0.88 C for 15-MHz at 1.025 W/cm^2; and 0.79 C for 15-MHz at 0.775 W/cm^2.

Results of a followup examination of several of the rhesus monkeys exposed 11 months earlier to 15- and 20-MHz radiofrequency radiation (*@MR1565*) were reported by Krupp (*@MR1566*) in 1978. Measurements were made of packed cell volume, hemoglobin, leukocyte count, percentage of segmented cells, percentage of lymphocytes, and other variables. These were compared with data obtained from unexposed animals housed under similar conditions and with values reported in the literature, since no preexposure values were available for the original group. Krupp felt that there were no significant differences. This was likewise true for a second group of animals exposed to 26-MHz radiation for 6 hours at 500, 750, and 1,000 mW/cm^2 up to 21 months previously.

Effects on the Immune Response

A considerable amount of research has been directed toward determining the effect of RF and microwave irradiation on immunologic mechanisms (Table III-11). Several reports dealing with alterations in WBC count are discussed in Hematologic Effects and in General Physiologic and Other Effects. In addition, a study by Huang et al (*@MR1663*), showing a dose-dependent reduction in the number of mitogen-stimulated lymphocytes undergoing mitosis,

TABLE III-11

IMMUNOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions ($mW/sq\ cm^2$)*	Duration	Remarks	Reference
Mouse	0.026	800	15 min; 15 min, 2 x d for 10 d	Decrease in thymus weight; increase in corticoid levels, number of T- and B-cells; suppression of delayed hypersensitivity reaction after multiple exposure	Liburdy (*@MR2214*)
"	0.462	1	15 min/d for 20 d	Decreases in phagocytic activity and index complement and lysozyme titers, bactericidal activity of skin, and leukocyte concentration; resistance to Typhus abdominalis infection declined; decreases in antibody titer and in antibody-forming cells in spleen; microscopic changes in thymus, spleen, and lymph nodes	Zalyubovskaya and Kiselev (*@MR3066*)
"	2.45	14 mW/g (controlled temperature and relative humidity)	30 min	No change in T- and B-cell number; increase in mitogenic response of B-cells	Wiktor-Jedrzejczak et al (*@MR1134*)
Mouse (18)	2.45	0.6 W at 12.3-15.6 mW/g	"	Increase in CR-bearing lymphoid spleen cells, no change in spleen cell number	Wiktor-Jedrzejczak et al (*@MR0394*)
Mouse	3	40 (far field)	2 h/d for 7 d	Decrease in number of herpes and vaccinia virus lesions	Luczak et al (*@MR2172*)
"	9.4 (PW; 17-MHz modulation)	0.095 mW	6 h/d for 3 d	Progress of trypanosomal infection slowed	Berteaud et al (*@MR0780*)

TABLE III-11 (CONTINUED)

IMMUNOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	0.01488	100 V/m	4 h/d for 10 mo	Increase in phagocytic and bactericidal activity at 1 mo; increase in inflammatory response	Volkova and Fukalova (*@MR2673*)
"	0.01488	2,250 V/m	1 h/d for 10 mo	"	"
"	0.0149	200	60 min/d for 2.5 mo	Increase in phagocytic activity at 25 d followed by decrease	Smurova (*@MR1390*)
Rat (10)	0.026	8,620 (23.0 W/kg)	--	Suppression of inflammatory response, decrease in lymphocytes and increase in neutrophils	Liburdy (*@MR2052*)
Rat	0.0395	60	60 min/d for 2.5 mo	Increase in phagocytic activity at 25 d followed by decrease	Smurova (*@MR1390*)
"	2.38	10	"	Maximal increase in phagocytic activity	"
Rat (140) and rabbit (30)	0.05	0.5-6 V/m	10-12 h/d for 180 d	Decrease in phagocytic activity	Serdiuk (*@MR2518*)
Rat	2.45	5, 25	10, 20 min/d on 6th-15th d of pregnancy	Increases in thyro-binding and iron-binding capacities and in serum iron; decrease in thyroid hormone and increase in protein trans-ferrin	Vetter (*@MR2982*)
"	2.425	80 W	5 min	Giant mast cell production	Valtonen (*@MR1467, @MR1468*)

TABLE III-11 (CONTINUED)

IMMUNOLOGIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	2.45	100	8-15 min/d, 1 d/wk for 7 wk	Autoimmune response suppressed	Kamat (*@MR1857*)
"	3	1	1 h/d for 6.5 mo	Temporary increase in phagocytosis and bactericidal activity	Sokolova (*@MR2662*)
Hamster (80)	2.45	5-45	15 min/d for 5 d	Dose-dependent reduction in mitogen-stimulated lymphocytes undergoing mitosis	Huang et al (*@MR1663*)
Guinea pig (100)	3 (PW and CW)	3.5	3 h/d for 3 mo	Nuclear disintegration in lymphoblastoid cells	Baranski (*@MR2603*)
Guinea pig (16)	"Radar" (1-10 GHz)	100 W	1-h session, 3 x d for 10 d	Decrease in agglutinin titer measured over 4 wk after start of irradiation	Sacchitelli and Lerza (*@MR2688*)
Guinea pig (100) and rabbit (100)	3 (CW and PW)	3.5	3 h/d for 228 h	Increase in mitotic indices in spleen and bone marrow	Baranski (*@MR0169*)
Guinea pig and mouse	2.95 (CW and PW)	3	2 h/d for 37 or 79 d	Increase in lymphoblastoid cells, plasmocytes, antibody-producing cells	Czerski (*@MR0185*)
Mouse (200)	2.95 (PW)	0.5±0.2	2 h/d, 6 d/wk, for 6 wk	"	"
Rabbit (10)	3	3 (far field)	6 h/d for 6 wk or 3 mo	Impairment of granulopoiesis following bacterial infection	Szmigielski et al (*@MR0050*)
Rabbit (20)	"SHF"	0.01, 0.05	4 h/d for 4 mo	Decrease in antibody titers at 0.05 mW/cm^2	Dronov and Kiritseva (*@MR0200*)

*Unless otherwise specified

is discussed in detail in Carcinogenicity, Mutagenicity, and Effects on Reproduction. The results included in this section deal with alterations in phagocytosis as discussed by Sokolova (*@MR2662*) and Serdiuk (*@MR2518*), cell ultrastructure as described by Baranski (*@MR2603*), and antibody titer as measured by Sacchitelli and Lerza (*@MR2688*).

According to a 1967 report by Smurova (*@MR1390*), RF fields of moderate to high intensity elicited a biphasic bactericidal response from rat phagocytes. Three test groups, each consisting of 10 adult males, were irradiated 60 min/d for 2.5 months and compared with separate control groups. The first group was irradiated with 14.9-MHz shortwaves at 200 mW/cm^2; the second, with 39.5-MHz ultra-shortwaves at 60 mW/cm^2; and the third, with 2.38-GHz microwaves at 10 mW/cm^2. Blood was removed prior to, and at specified days during, the course of the 66-day exposure period and mixed with a live bacterial suspension. The general nature of the response to irradiation consisted of a primary phase of stimulation or activation of phagocytic activity followed by a secondary refractory and plateau phase. By the 7th day of irradiation with shortwaves of high intensity (group 1), the percentage of bacteria phagocytized and digested had increased to, respectively, 10 and 40% above control values, whereas the phagocytic and digestive indices had increased by 50 and 80%.

These results indicated that not only were more cells participating in phagocytosis and digestion but also that the number of bacteria absorbed per cell was greater (*@MR1390*). The phagocytic activities of the groups exposed to higher frequency radiation at lower power densities reached higher but similar maxima later, ie, at 25 days. These four measures of phagocytosis fell below control values thereafter, with the lowest level (40%) attained by group 1. One month after irradiation ended, the indices had returned to control values. The bactericidal property of the phagocytes was not significantly altered by irradiation with shortwaves. Ultra-shortwave and microwave irradiation, on the other hand, lowered bactericidal ability to approximately 80% of control levels at the 25th day of irradiation in the first group and to 70% at the 43rd day in the second. Smurova considered the radiation effect to be moderate and reversible, with the strength and rate of the compensatory reaction dependent on wavelength. No dependence on power density was observed.

A 1967 report by Volkova and Smurova (*@MR2850*) indicated frequency-dependent changes in the phagocytic activity of neutrophils following long-term (6-month) irradiation of rats. Decreases in cell absorption and total bactericidal activity were more pronounced with HF radiation than with VHF radiation. A biphasic response was also described by Volkova and Fukalova (*@MR2673*) in a 1974 report on the effect of shortwave irradiation (14.88 MHz) on the phagocytic activity of rat leukocytes. Three groups of rats were compared for 10 months for their response to an infection with a 24-hour agar culture of <u>Escherichia coli</u>: a control group, one group irradiated for 4 h/d at 100 V/m, and one for 1 h/d at 2,250 V/m. A doubling of phagocytic activity was found at 1 month with both irradiation schedules. This was followed by decreases of 25 and 56% of the initial activity during the 2nd month of irradiation with 2,250 and 100 V/m, respectively. Phagocytic activity then rose to maxima at the end of 3 and 6 months, respectively, before falling to final values of 75 and 40%. No recovery occurred within 1.5 months after irradiation. The bactericidal activity followed similar increase-decrease patterns. When the same groups were reinfected 9 months after irradiation had ended, the degree of inflammation was observed to be greater in the irradiated animals and to take longer to subside. Sokolova (*@MR2662*), in 1974, reported multiphasic responses of the phagocytic and bactericidal activities of rats irradiated with 3-GHz microwaves at 1 mW/cm^2 for 1 h/d.

In a 1970 report of the treatment of experimental trypanosomiasis in rabbits, Pautrizel et al (*@MR1233*) noted that irradiation with electromagnetic energy, combined with an H-field pulsed at a low rate, induced an increase in the albumin:globulin ratio within the blood plasma (which had been lowered by the trypanosomiasis) to control values. This return occurred within 1 month after irradiation for 12 h/d during either 1 or 3 weeks was halted. With the first course of irradiation, survival of the animals was prolonged whereas, with the second, the animals were cured of the infection. Although the rabbits retained their capacities for producing the antibodies necessary for complement formation for over a year, the rate of generation of agglutinating antibodies diminished. Identical experiments with mice yielded similar results (*@MR1232*). In 1971, Berteaud et al (*@MR0780*) studied the progress of a parasitic infestation (*Trypanosoma equiperdum*) in mice. The results indicated that near-field irradiation begun 50 hours after inoculation slowed the development of the infestation. One noteworthy observation was that CW radiation under similar conditions was ineffective in suppressing the infection.

Szmigielski et al (*@MR0050*), in 1975, showed that nonthermogenic microwave irradiation inhibited the granulopoietic response to bacterial infection in rabbits. Three sets of five adult animals each (one control, one irradiated for 6 h/d for 6 weeks, and another irradiated for 6 h/d for 3 months) were compared for various functional aspects of the granulocyte response to an acute staphylococcal infection. The animals were placed in an anechoic chamber and were irradiated under far-field conditions with 3-GHz microwaves at 3 mW/cm^2. Intravenous infection followed irradiation; and granulopoiesis was analyzed prior to, and at 4, 6, 10, and 14 days after, infection.

Following microwave irradiation, Szmigielski et al (*@MR0050*) observed that the clinical course of the bacterial disease was more serious. The 6-week course of irradiation induced greater leukocytosis and granulocytosis at 4-6 days following infection. The approximately 25% greater concentration of granulocytes in the blood decreased to 25% of control values by 10 days. The results indicated that, following 6 weeks of exposure, granulocytes from irradiated animals were as reactive as those obtained from control rabbits, and that the release of mature competent granulocytes into the blood serum was similar under both conditions, but that the regeneration and maintenance of a reserve pool of granulocytes in the bone marrow were impaired by irradiation.

Irradiation for 3 months, on the other hand, inhibited the response completely (*@MR0050*). There was no stimulation of release of granulocytes into the blood similar to that seen during the control infection (usually an immediate 50% increase in concentration), and the concentration gradually declined during the 14-day period to 50% of the control values. Following a 6-week exposure, granulocytes released into the blood had decreased lysozyme activity and ability to reduce nitro blue tetrazolium compared with those in controls. Three months of irradiation before infection almost completely inhibited the increase in lysozyme activity; however, reduction of the dye was actually increased above the control level.

Szmigielski and coworkers (*@MR0050*) attributed the increased lysozyme activity to stimulation of granulopoietic kinetics and the increased reduction of dye to increased intracellular oxidative metabolism and glycolysis. The most noticeable effect was in the bone marrow. The concentration of granulocytes decreased to 75% of initial values within 14 days following irradiation for both 6 weeks and 3 months; during the same period, control animals had a 50% increase. An increase in the concentration of immature forms (promyelocytes, myelocytes, and metamyelocytes) was evident in the marrow of the irradiated animals.

In 1976, Luczak et al (*@MR2172*) reported that irradiation of mice for 2 hours on each of 7 days after infection with herpes or vaccinia viruses decreased the number of viral lesions. Microwaves with a frequency of 3 GHz were used at a far-field power density of 40 mW/cm^2.

According to a 1977 study by Hamrick et al (*@MR0211*), microwave irradiation of Japanese quail during embryogenesis did not affect humoral immunity in later stages of life despite the known susceptibility of developing immunobiologic tissues to damage by various environmental and biologic insults. Fertilized quail eggs were placed in a Plexiglas chamber lined with microwave absorber and exposed to CW 2.45-GHz radiation at 5 mW/cm^2 for the first 12 days of development. A total of 77 quail hatched from microwave-irradiated eggs was compared with 40 quail hatched from sham-irradiated eggs. At 5 weeks, each quail was injected with sheep red blood cells (SRBC's) and bled prior to, and 4 days following, injection. No difference in the levels of anti-SRBC hemagglutinins was detected. After the final bleeding, the bursa of Fabricius (lymphoid tissue) and the spleen were removed and weighed. There were no differences between the weights of the organs from control and irradiated quail.

Valtonen (*@MR1468*), in 1966, observed giant mast cells in the peritoneal cavities of rats exposed to microwave radiation. Three hours after irradiation, giant mast cells with a mean diameter of 37 µm and a maximum diameter of 47 µm were found to make up 5-30% of the total mast cell population. The disruption or degranulation observed under other abnormal conditions was not evident. Since the rectal temperatures of the irradiated animals increased to approximately 41 C during the exposure, a second group of rats was maintained in a temperature-controlled chamber until rectal temperatures reached 42 C. These rats were also examined, but there was no evidence of altered mast cell morphology.

In a 1975 compilation of the results of various experiments dealing with the effects of low-power microwave irradiation on the immune system, Czerski (*@MR0185*) emphasized the dissimilar ways in which the various components of the lymphocytic system respond to microwaves. Irradiation of guinea pigs and mice with 2.95-GHz microwaves at 3 mW/cm^2 for 2 h/d was found to disrupt the circadian rhythm of lymphocyte mitosis. The production and action of immuno-competent lymphocytes were tested in a series of experiments with young adult male mice. Pulsed microwaves (pulse width 1 μs, pulse repetition rate 1,200 pps) at a power density of 0.5 mW/cm^2 were used. Two groups of mice, one exposed for 6 weeks and one for 12, were compared for their responses 6-8 days following injection with $2x10^6$ SRBC's; controls were either sham irradiated and immunized or irradiated and not immunized. The numbers of lymphoblastoid cells in the lymph nodes, of plasmocytes, and of antibody-producing cells were significantly greater in animals exposed for 6 weeks than in animals not irradiated or irradiated for 12 weeks. When the percentage of lymphoblastoid cells in peripheral blood was determined monthly during a 6-month exposure to pulsed microwaves at a mean power density of 5 mW/cm^2, a spontaneous increase to 10.5% from control levels of 2.8% was observed at 1-2 months and a smaller increase (to 5.5%) at 7 months.

In a 1977 study, Wiktor-Jedrzejczak et al (*@MR0394*) found that 2.45-GHz microwaves induced an increase in the number of complement receptor (CR)-bearing lymphoid spleen cells in mice. Adult males were placed within a waveguide, maintained at constant temperature and relative humidity, so as to face the source. Rectal temperature was monitored and was never observed to change by more than ±0.5 C. In the first experiment, the spleens of 18 mice were removed at various times after the mice had been irradiated for 30 minutes, and the total numbers of cells were counted. The proportions of cells bearing surface immunoglobulins (Ig's), theta-antigens, and CR's were determined and compared with those determined for a sham-exposed group of mice. The only significant differences noted were in the frequency of CR^+ cells--an increase of 33.5% on day 6 in the irradiated mice. When the exposure schedule was increased to three similar irradiations, one every 3 days, CR^+ cell frequency was observed to rise to net increases of 24% on day 3, 52% on day 6, and 67% on day 9 postexposure. A 21.5% increase in Ig^+ cells was also noted on day 6. Since the total number of spleen cells did not vary during the course of the experiments, these increases could not be attributed to general cell proliferation. The exposures were limited to near-field conditions.

Wiktor-Jedrzejczak et al (*@MR1134*), also in 1977, investigated the effect of microwave irradiation on the frequency and function of the T- and

B-cell subpopulations of lymphocytes in the spleen. Adult male mice were irradiated with 2.45-GHz continuous microwaves for 30 minutes at an SAR that averaged 14 mW/g. A constant environment was artificially maintained in the waveguide to ensure that the maximum average change in rectal temperature of the exposed mice never exceeded 0.2 C. Sham-irradiated controls were placed in polystyrene holders and handled similarly to irradiated mice. Neither a single 13±2.5 mW/g exposure nor a series of three irradiations 3 days apart significantly increased the frequencies of occurrence of T- and B-cells above those for control mice 6 days after irradiation. The frequency of CR^+ cells was increased by 24-29% by the single exposure and by 52-64% by the three exposures. When splenic cells from irradiated mice were cultured in mitogen-containing media and the uptake of tritiated thymidine into DNA was determined at 3, 6, and 9 days postexposure (DNA synthesis used as a measure of mitogenesis), a differential effect of microwaves was detected. There were no significant differences between irradiated and sham-exposed animals in the response of T-cells to phytohemagglutinin P or concanavalin A. However, B-lymphocytes from the microwave-irradiated mice differed from those of controls in their responses to three of the four mitogens used. The 12-27% increases in irradiated mice were statistically significant; triple exposures did not quantitatively alter the response from that observed after the single exposure.

Mice injected with sheep erythrocytes or dinitrophenol-lysine-Ficoll and then irradiated with 2.45-GHz microwaves for 30 minutes on 3 successive days produced fewer antibodies to the thymus-dependent (significant decrease) or thymus-independent (nonsignificant decrease) antigens on the 4th day after injection than did sham-irradiated controls (*@MR1134*). The results indicated that microwaves have no effect on the T-cell lymphocyte subpopulation, at least with regard to their production and their operationally defined functions. In contrast, specific clones of B-cells, namely, those bearing CR's and several others responsive to certain mitogens, were stimulated. This occurred, however, without microwave-induced general proliferation of lymphoid cells.

Liburdy (*@MR2052*), in 1977, studied the attenuation of the inflammatory response caused by preirradiation with RF fields. The experiments compared, under several exposure conditions, rats whose footpads had been inoculated with SRBC's and mice that had had their tails cut. The measured field strengths of the CW 26-MHz radiation were 5.78 kV/m and 6.71 A/m. The calculated power density, 8.62 W/cm^2, yielded average SAR's of 12.9 and 23.0 W/kg for mouse and rat, respectively. One group of traumatized animals was sham irradiated, and a second was exposed to a high temperature (79 C) in a vented hot-air oven. The durations of RF irradiation and of warm-air exposure were matched (4-7 and 8-12 minutes) to induce similar increases in rectal temperature, ie, 2-4 C. Liburdy attributed the suppressed hypersensitivity reactions to the observed peripheral lymphopenia and neutrophilia. Although the results indicated that the alteration of the cell-mediated immune response by RF irradiation was due to stress distinct from that commonly caused by convective heating, Liburdy considered that the RF exposure resulted in a uniform thermal stress that induced release of hormone from the HHA complex. This, in turn, caused the transient immunologic response. Specific heating, or local hot spots, should not have occurred with radiation at this frequency.

In a more extensive examination of the effects of RF irradiation on the immune system of the mouse, Liburdy (*@MR2214*) in 1978 concluded that the lymphopenia he observed was a secondary response to hyperthermia and was mediated at the cellular level through a steroid-associated mechanism. Young adult male mice were subjected to single (15 minutes) thermogenic (26 MHz, 800 mW/cm^2, 5.6 W/kg), single nonthermogenic (26 MHz, 50 mW/cm^2, 0.36 W/kg or 5 MHz, 800 mW/cm^2, 0.36 W/kg) RF irradiation, or multiple (15 minutes twice a day for 10 days) thermogenic RF irradiation. They were compared with mice maintained in thermogenic environments and mice treated with the steroid methylprednisolone sodium succinate (MPSS) to determine the extent of lymphopenia and of neutrophilia, alterations in corticoid levels and spleen and thymus weight, frequencies of occurrence of T- and B-lymphocytes, and immunosuppression of local delayed hypersensitivity. The pattern of response obtained with RF mimicked that observed on the introduction of glucocorticoids into the blood; thus, Liburdy hypothesized that whole-body RF irradiation acts as a heat stress that stimulates the HHA axis to trigger the release of adrenal steroids. The thermally induced rise in splenic B-lymphocytes observed in the above experiments resembled the effect noted by Wiktor-Jedrzejczak et al (*@MR0394*) for 2.45-GHz microwave radiation at 13 W/kg, an absorbed power more than twice the value used by Liburdy. Their experimental protocol actually allowed more efficient thermoregulation to occur and lessened the total thermal stress on the animals.

In a 1970 study designed to detect thermal effects of microwave irradiation, Kamat (*@MR1857*) tested the autoimmune response of rats after irradiation with a frequency of 2.45 GHz. An average power density of 100 mW/cm^2 was produced from an antenna horn located 100 cm in front of the animal to be exposed. One group of five rats was irradiated for 8 or 10 min/d, 1 d/wk for 4 consecutive weeks; a second group was irradiated for 15 min/d on the 3rd, 6th, and 8th days of the month and for 13 min/d on the 10th, 22nd, 24th, and 29th days. This irradiation was sufficient to raise the mean rectal temperature by 3.4 C in the first group and by 5.2 C in the second. Body and eye lens weights were unchanged, whereas the mean weight of the thyroid gland in irradiated animals was eight times that in control animals and the only histopathologic change observed was atrophy of the tubules of the testes. No serum antibodies against any of nine organ antigens (testis, lens, liver, spleen, lung, kidney, heart, thyroid, and brain) were detected. Thus, radiation at high power densities was incapable of sufficiently damaging cells to cause release of intracellular antigens or alteration of their autologous antigens. Thermal injury had been previously suggested to elicit an autoimmune response in the testes of guinea pigs.

Dronov and Kiritseva (*@MR0200*) discussed the inhibition of antibody production in a 1971 report on rabbits chronically exposed to SHF radiowaves. Rabbits were irradiated for 4 h/d for 4 months at 50 or 10 $\mu W/cm^2$ (the frequency of the radiation was not specified). Four sets of five rabbits each served as controls for comparison of agglutination reaction, indirect hemagglutinin reaction, and 19S and 7S antibody titers. No statistically reliable differences occurred between the controls and the rabbits irradiated at 10 $\mu W/cm^2$. Irradiation at 50 $\mu W/cm^2$ caused decreases in all the titers, the decreases becoming progressively more pronounced for irradiation during, after, and before injection of the antigen. Dronov and Kiritseva concluded that prolonged exposure to low-intensity radiowaves, such as could occur under industrial conditions, caused a significant decrease in immunologic competence.

Effects on the Skin

Gersten et al (*@MR0744*), in 1949, described the effects of 2.45-GHz microwave radiation on tissue temperature and peripheral blood circulation in 50 volunteers. The muscle (1.5 cm deep), subcutaneous, and skin surface temperatures in the forearm increased by 6.7, 5.8, and 4.8 C, respectively, at an output power of 80 W and by 6.6, 5.4, and 5.0 C at 60 W. Temperatures rose sharply during the first 5 minutes of irradiation at 80 W, plateaued between 10 and 20 minutes of irradiation, and thereafter decreased. With 60 W, the increase in temperature was gradual during the first 20 minutes.

Concomitant with the temperature rise induced by 80-W irradiation, blood flow in the arm rose to a maximum of 67% above control levels at 30 minutes' exposure (*@MR0744*). A 30% increase was observed in blood flow after 15 minutes' exposure at 60 W. No harmful skin effects were noted during these experiments. Sensations of warmth were reported, followed by a subjective judgment of cooling during the later stages of exposure. This was attributed to increased blood circulation. The lower skin temperature noted after 30 minutes' exposure at 80 W, as compared with that observed following irradiation at 60 W, was correlated with this increase in circulation to the periphery.

By using a Mycalex (mica dust bonded with borosilicate glass) cylinder that had an impedance similar to that of skin, Gersten et al (*@MR0743*) were able to show, in 1950, that skin reflects a large fraction of the incident 2.45-GHz microwave energy. Temperature measurements made at, and 1 cm below, the external skin surface of the forearms of nine men were compared at two sites, one covered with Mycalex during irradiation and one not. After a 1-minute exposure at 80-W power at a distance of 5 cm, the covered region was hotter: 2.35 and 2.21 C greater for the skin and muscle, respectively, than the control preirradiation temperature. The Mycalex cylinder had essentially no temperature increase when exposed to the microwave field. Reflection by the skin was efficient in reducing the superficial and internal heating caused by microwaves and seemed to delay the onset of cooling normally effected by increased blood circulation.

Using the tissue clearance of sodium as a measure of local circulation, Millard (*@MR1099*), in 1955, showed that the increase in blood flow in the skin caused by shortwave diathermy was four times that in muscle. Radioactive ^{24}Na was injected into the quadriceps femoris muscle or into the overlying subcutaneous tissue of 46 persons. They were then treated with a diathermic apparatus for 20 minutes, by which time skin temperature had risen 5.3 C. The rate of skin clearance of ^{24}Na increased by 150% and that of muscle by 36% over rates observed in nonirradiated control subjects.

Experiments by Cook (*@MR0548*), in 1952, on skin heating in response to microwave irradiation indicated that skin temperature increased with increased dose, ie, higher power density or longer irradiation time, in a linear manner when blood circulation was inhibited. This was found to be true for both PW 3-GHz and CW 3.19-GHz microwave radiation. Temperature increases of more than 14 C up to the pain threshold of 45 C were noted. Temperature profiles constructed for various depths below the skin surface revealed a minimal increase at 0.5 cm within the fatty tissue, followed by a maximal increase at 1 cm within the muscle.

Cook's (*@MR0547*) 1952 estimate of the pain threshold for 3-GHz microwave radiation described measurements made on six subjects irradiated at five different sites on the body surface. Pain occurred when the skin temperature reached an average of 46 C. This was true for exposed areas of 9.5 and 53 cm^2; however, the power required to evoke the response was 45% greater for the smaller than for the larger area at similar exposure times. The most significant result was that the temperature corresponding to pain did not vary with area and time of exposure, radiation intensity, and anatomic site. Thus, pain is a poor quantitative measure of the intensity of radiation received.

In a series of reports spanning 1964 through 1975, Lehmann et al (*@MR2122,@MR2409,@MR2411,@MR2406*) discussed the heating patterns produced in humans by UHF radiation. Irradiation at 2.45 GHz was found to be less effective in initial heating of deeper tissues than was irradiation at 900 MHz, but irradiation at 434 MHz was no more effective than that at 900 MHz. A second observation revealed that the greatest increases in temperature occurred at depths of 2 cm within the muscle layer and that increased blood flow produced greater cooling in the surface and subcutaneous layers. Stevens and Peluso (*@MR0381*) observed in 1976 that temperature elevations induced in the thighs of 20 men after irradiation at 50 W for 10 minutes with 2.45-GHz microwaves were still evident 15 minutes later. The temperature changes ranged from 2.5±0.6 C at the surface to 1.9 C at a depth of 11 mm and 1.0 C at 21 mm.

In 1958, Vendrik and Vos (*@MR1940*) reported that, for 3-GHz radiation at 300-2,500 mW/cm^2, the minimum change in surface temperature that could be sensed was 0.2-1 C. In a 1963 report on the mechanism of temperature sensation, Hendler et al (*@MR0990*) used a 10-GHz microwave pulse generator to heat a 37-cm^2 area of the foreheads of four subjects. Skin temperature increases were linear with the intensity of radiation for six exposure durations but never exceeded 1 C. The 10-GHz radiation was found to be 50% as efficient in producing a temperature elevation as was IR radiation of similar intensity.

In contrast to the regularity of skin temperature changes induced by microwaves, the observations of temperature sensation were variable (*@MR1940*). Sensations of warmth occurred less than 0.5-3.5 seconds after rapid rises in skin temperature. The sensations did not cease when the skin temperature began to drop. Although the intensity required to elicit a sensation of warmth was inversely related to the duration of exposure, the actual temperature change associated with that sensation increased with the length of exposure. Thus, the sensation of warmth was not wholly attributable to a temperature change caused by microwave heating. Furthermore, the contrast between the smaller temperature increases produced by microwave radiation and the greater increases by IR radiation at increasing depths below the skin surface implied a more substantial difference in heating between superficial and interior layers. In a comparison with the report by Vendrick and Vos (*@MR1940*), Hendler et al (*@MR0990*) attributed the five times greater energy flux necessary to induce a sensation of warmth with 3-GHz (10-cm) microwaves over that required with 10-GHz (3-cm) waves to the fact that the former penetrate five times as far into tissue. According to Hendler et al, the substantial energy reflections from various subcutaneous areas would have complicated the internal heat distribution patterns and made distinction of warmth difficult.

In 1966, Schwan et al (*@MR1327*) reported measuring the elapsed time before each of four subjects could perceive a sensation of warmth in a 7-cm-diameter area of forehead exposed to 2.88-GHz microwaves. The subjects were irradiated at two power densities, 56 and 74 mW/cm^2, for a minimum of 30 exposures each (five or more times per experiment, twice a day), and their reaction times were measured. Theoretical calculations (based on a 1-cm depth of penetration for 10-cm microwaves) indicated that skin thickness, which ranges from 0.2 to 0.6 cm in humans, could affect the amount of heat developed throughout the skin (*@MR0547,@MR0990*). If this could in turn affect the perception of warmth, then variability in the reaction times would be expected. The times measured for the four subjects varied between 10 and 100 seconds for an incident power density of 75 mW/cm^2. Their average times ranged from 15 to 73 seconds, with respective standard deviations of 6.2 and 19.8 seconds. Schwan et al (*@MR1327*) concluded that reaction times are not linearly proportional to the reciprocal of the incident power density and, thus, that subjective awareness of warmth is not a reliable indication of microwave hazard.

In support of their hypothesis of "micro heating," Osipov and Kalyada (*@MR1178*) presented evidence of localized skin heating following irradiation with microwaves at power densities three orders of magnitude lower than that previously considered to be necessary for whole-body thermogenesis. The wrists of 24 young women were irradiated 1 hour a day for 15-21 days with CW and PW 3-and 10-GHz radiation at power densities of 10 and 20 $\mu W/cm^2$. A temperature increase of less than 1 C was observed but was judged to be significant when compared with the increase produced in control subjects irradiated for 1 h/d for 6-12 days. The general pattern of response included an initial decrease followed by a slow rise beginning at 5-10 minutes of irradiation. In subjects with an occupational history of exposure to microwaves, the response was a continual increase to a higher level, which was directly proportional to the length of prior industrial service. Osipov and Kalyada suggested that small-scale heating of selected bodily tissues occurs during microwave irradiation. This is then reflected in complex nervous system reflexes, secondary humoral responses, and, finally, overall functional changes.

In 1973, Brodkin and Bleiberg (*@MR0010*) described two cases of dystrophy of fingernails in two cafeteria workers who had operated a microwave oven that generated 2.45-GHz radiation. One worker had been using the oven for 4 years and the other for 1.5 years. Previous histories indicated no other underlying physical problems, and the lesions began to improve when the oven was removed. No measurements could be made of oven leakage, since the employer removed the oven after hearing of the workers' complaints. In 1976, the two workers requested that a suit that they had brought against one microwave oven manufacturer be dismissed due to lack of evidence that leakage from the oven was responsible for the injuries (V Blaha, written communication, November 1978). Nevertheless, during a 1978 visit to a Scranton, Pennsylvania, plant in which RF sealers were being used, NIOSH representatives observed several cases of fingernail deformities in the operators of the sealers (P Ruggera et al, written communication, January 1979).

General Physiologic and Other Effects

Many of the results discussed here appear in the relevant tables provided for other sections of this chapter.

(a) Thermoregulation

Richardson et al (*@MR1268*) showed in 1950 that irradiation with 18.8-MHz shortwaves and 2.45-GHz microwaves induced temperature increases within the hindleg muscles of dogs as well as increases in blood flow. Herrick and Krusen (*@MR0996*), in a 1953 study of the physiologic and pathologic effects of 2.45-GHz radiation, ascribed the observed changes to heating of tissues. In a 1959 investigation of the process of heat exchange in mice, Jacobson et al (*@MR1755*) analyzed the dependence of the microwave-induced rise in rectal temperature on power and energy densities. Adult mice were irradiated with 9.27-GHz microwaves, and their rectal temperatures were monitored. The increase in temperature was observed to be linearly dependent on the energy density of the incident radiation but independent of power densities above 100 mW/cm^2; below that value, the temperature increase was directly proportional to the power density used.

Samaras et al (*@MR1301*), demonstrated in 1971 that continuous irradiation of adult rats with 2.45-GHz microwaves at 80 mW/cm^2 caused an increase in rectal temperature to an average of 45 C and death within 17±1.8 minutes. When the ambient temperature in the anechoic irradiation chamber was controlled so that the rats were maintained in a rectally isothermic state (39±1 C), the animals survived for the duration of the experiment, ie, 3 hours. No abnormal clinical signs were evident either immediately following irradiation or 30 days later. The results indicated that the lethal action of the radiation depended on a thermal, rather than a nonthermal, effect.

Using adult rats, which have a basal metabolic rate (BMR) of 8.16 W/kg, Houk et al (*@MR0835*), in 1973, reported that irradiation with microwave energy at a power density sufficient to approximately triple the rate of heat production leads to thermal stress. Young adult males were irradiated in groups of 8 (total number at least 344) for 2.5 hours with 2.45-GHz continuous microwaves in an environmentally controlled chamber. Irradiation at 9 and 18 mW/cm^2 did not visibly affect the rats' behavior; the rectal temperatures, which increased by 0.5 and 1.5 C, respectively, returned to normal within 30 minutes after irradiation stopped. Heat stress was evident in rats irradiated at 36 mW/cm^2. The rectal temperature of these rats increased by nearly 3 C within the first 0.5 hour of irradiation and required 1 hour to return to normal after irradiation was halted. Houk et al interpreted their results as indicating an involvement of hypothalamic regulatory centers in microwave-induced thermogenesis.

Differences between normal and hypophysectomized animals were observed by Prausnitz and Susskind (*@MR0898*) in a 1959 analysis of temperature regulation in mice and rats irradiated with 10-GHz microwaves. There was a smooth increase in rectal temperature for hypophysectomized rats continuously irradiated at 60 mW/cm^2 or less. Normal mice, on the other hand, showed periodic increases and decreases in temperature that approached a steady state below the lethal temperature (not given). The final temperature depended on the power density. A narrow range was determined for the rate of intermittent exposure above which the body's homeostatic mechanisms are overloaded and progressive thermogenesis ensues and below which the stimulatory effect of a second exposure on the cooling rate induced by the first is lost.

In six series of irradiations at power densities ranging from 7 to 110 mW/cm^2, Tolgskaya et al (*@MR2548*), in 1959, reported power density-dependent effects in rats, such as edema, hemorrhaging, and degeneration of the liver, kidneys, and nervous system. All experiments were performed with 3-GHz microwaves, and deleterious effects were noted after irradiation at all power densities used above 19 mW/cm^2. Evidence of cell proliferation accompanying the degenerative tissue changes was obtained during morphologic examinations.

Results of a comprehensive study on the acute effects of microwave irradiation on several animal species were described by Deichmann et al (*@MR0194*) in 1959. Animals were placed, one at a time, in a small anechoic chamber and were irradiated with 24-GHz microwaves. Power densities of 260 mW/cm^2 and below were used in the far-field region. Hyperactivity and convulsions were evident during irradiation, and erythema and burning of the skin occurred at power densities above 100 mW/cm^2. The abdomen was found to be more susceptible to localized radiation than were the back and head; irradiation of the head required a 50% longer exposure to kill than did irradiation of the abdomen. The pathologic changes produced by irradiation of the three regions differed. For example, burning did not occur in the lumbar region, but there was more severe damage to the major internal organs than was observed after irradiation of the head. With rats and mice, death occurred when the rectal temperature reached 43.0±0.5 C, regardless of the power density and duration of exposure. In general, the temperature increased more rapidly at higher power densities, ie, 30 minutes for 109 mW/cm^2 vs 4 hours for 43 mW/cm^2, and was more rapid in the directly exposed area than in other regions. The temperature increase was greater in the stomach than in the spleen, kidneys, and liver (5.75, 5.0, 4.5, and 3.75 C, respectively, after 25 minutes' exposure at 75 mW/cm^2). In contrast, a 1973 report by Rotkovska et al (*@MR0042*) demonstrated that the hearts and livers of mice irradiated with 2.45-GHz microwaves at 260 mW/cm^2 were the first organs in which temperature increases could be recorded.

Observations of chicks exposed under the same conditions revealed behavioral changes as well as dehydration (*@MR0194*). Finally, at similar power densities, continuous and intermittent (at 50% of the continuous energy fluence, or dose) exposures were found to kill rats in approximately the same time, whereas intermittent irradiation at 17% of the total dose doubled the period of survival. In an attempt to contrast the hyperpyrexia produced by microwave radiation to that observed following IR radiation, Deichmann et al determined the power density of IR radiation required to produce temperature increases in rats similar to those observed with microwaves. At a power density of 0.3 W/cm^2, IR radiation was approximately 0.27 times as efficient as 24-GHz microwave radiation in raising temperatures in the rectal and lumbar region.

Using oxygen consumption as a measure of thermal stress, Ho and Edwards (*@MR2003*), in 1977, discussed the metabolic response of mice to microwave irradiation. At power levels producing mean SAR's above the BMR of 9 mW/g, the mice adjusted their metabolic rates downward during the irradiation, thereby decreasing their rates of oxygen consumption and microwave absorption. The mechanism responsible for this compensatory reaction during irradiation at thermogenic energy dose rates was not examined. Further studies on this effect are detailed in the section on behavioral effects dealing with "avoidance."

In 1976, Cleary and Wangemann (*@MR2018*) invoked thermogenesis as the cause for the decrease in sodium pentobarbital-induced sleeping time observed in microwave-irradiated rabbits. Far-field exposures in a temperature-controlled anechoic chamber led to a statistically significant, power density-dependent analeptic effect at 5 mW/cm^2 and above for 2.45-GHz and at 10 mW/cm^2 and above for 1.7-GHz irradiation. Sleeping time decreased from 50 minutes to 15 minutes at 25 mW/cm^2 with 2.45-GHz and to 20 minutes at 50 mW/cm^2 with 1.7 GHz radiation. Rectal temperature was observed to rise with exposure at increasing power densities of 1.7- and 2.45-GHz radiation. Linear regression analysis of both sets of data suggested that sleeping time was related to the change in temperature. Thermal stress was postulated to account for the temperature elevation; however, a comparison of anesthetized animals subjected to microwave irradiation at 10 mW/cm^2 and to hot-air heating at 39 C, both sufficient to induce a temperature rise of 1 C, indicated that sodium pentobarbital-induced sleeping time was not decreased by heating. Cleary and Wangemann suggested that differences in the distribution and rate of energy absorption were responsible for the dissimilar effects of radiation and heating and provided data on the rate of temperature increase to support this claim.

Activation of thermoregulatory mechanisms in rhesus monkeys by high-power density 26-MHz radiation was described by Frazer et al (*@MR1626*) in 1976. Thermal equilibrium was attained within the 1st of 6 hours of irradiation at power densities of up to 1,000 mW/cm^2. Small increases in rectal (0.8 C) and skin (2.0 C) temperatures were observed. Extrapolation based on relative SAR and BMR values and scaling suggested that humans should be able to tolerate an extra thermal load imposed by 26-MHz irradiation at 400 mW/cm^2 as easily as the monkeys tolerated the 1,000 mW/cm^2 RF field.

The capability of rhesus monkeys to compensate for the thermal load induced by microwave irradiation was described by Krupp (*@MR1565*) in 1977. Ten animals were placed one at a time into a plastic cage above a coaxial transmission line so that both the long axis of each animal and the E-vector were vertical. Rectal temperatures rose rapidly during the first 30 minutes of exposure to continuous HF radiation and then leveled off for the remaining 2 hours of the experiment. The average maximum increases induced were 1.60 C for 20-MHz radiation at 1.27 W/cm^2, 0.92 C for 20-MHz at 0.76 W/cm^2, 0.88 C for 15-MHz at 1.025 W/cm^2, and 0.79 C for 15-MHz at 0.775 W/cm^2. Comparable exposure conditions for humans were calculated to be frequencies of 8 and 5 MHz and power densities of 225 and 150 mW/cm^2. These data suggest that exposure at levels 15-25 times the present limit (of 10 mW/cm^2) ought to be tolerated for 3 hours with only a small rise in body temperature, and, thus, should not place an undue thermal burden on humans. Results of a hematologic examination of several of the rhesus monkeys performed 11 months later by Krupp (*@MR1566*) revealed no differences between irradiated and unirradiated animals.

(b) General Physiology

Observations on the physiologic aspects of microwave irradiation of dogs were made by Michaelson et al (*@MR0258*) in 1961 and by Michaelson (*@MR0251*) in 1970. Young adult animals, constrained by a Plexiglas holder in an anechoic chamber, were irradiated with 2.8-GHz pulsed microwaves. Weakness followed by collapse occurred within 4-6 hours at 100 mW/cm^2 or 2-3 hours at 165 mW/cm^2 (*@MR0251*). During irradiation at 165 mW/cm^2, rectal temperatures increased initially by 1-2 C, stabilized for 40 minutes, and then increased another 2-3 C. Irradiation at 100 mW/cm^2 produced some inital heating but no eventual rise in temperature. Variations in body size, ranging from 4 kg for small dogs and rabbits to 20 kg for larger dogs, did not influence the pattern and amount of temperature increase produced by 2.8-GHz microwaves at 165 mW/cm^2. Skin burns were observed. After 4.5 hours of irradiation, body weight had decreased 6% at 100 mW/cm^2 and 8.5% at 165 mW/cm^2. Hematocrit values increased at the same time, suggesting dehydration.

The physiologic response of dogs to pulsed (2-µs pulse width, 360 pps) 1.24-GHz microwaves was described by Michaelson et al (*@MR1090*) in 1967. Twenty-one young adult animals were exposed at 50 mW/cm^2 for 6 h/d for 5 consecutive days. During this period, loss in body weight, retching and vomiting, and elevation of rectal temperature were observed. These changes are indicative of a generalized response to an imposed thermal stress; however, between the times of the first and the fifth exposure, the loss in weight during irradiation progressively decreased from an average 3.22 to 2.51% and the preexposure rectal temperature decreased from 101.7 to 100.6 C. The actual increases in temperature induced by irradiation ranged from 0.06 to 0.67 C.

Michaelson et al (*@MR1090*) stressed that their results indicated functional changes in the central nervous, neuroendocrine, and cardiovascular systems without appreciable thermal effects or overt incapacitation. They concluded that microwave irradiation affected the nervous system, the bone marrow, the kinetics of electrolyte regulation and fluid balance, pulmonary gas exchange, and thyroid and hypothalamic-pituitary activities. The relative contribution of thermal and nonthermal factors to the body's compensatory and homeokinetic mechanisms could not be determined, although the action of both was implied.

In a long-term study of the effects of chronic microwave exposure on dogs, Michaelson et al (*@MR0254*), in 1971, noted a number of frequency-dependent variables but no permanent physiologic changes. Two dogs were irradiated with PW 24-GHz microwaves (duty cycle $6x10^{-5}$) at 24 mW/cm^2 for 20 months--one for 6.67 h/d for 5 d/wk and the other for 16.5 hours on each of 4 days weekly. Irradiation of nine dogs with PW 1.29-GHz microwaves (duty cycle $1.08x10^{-3}$) at 20, 50, or 100 mW/cm^2 was either for 6 hours or for 6 h/d, 5 d/wk for 2-4 weeks. Temperature measurements were made while the dogs were in the Plexiglas restraining cages within the anechoic exposure chamber. Multiple 24-GHz irradiation led to a decrease in body weight of 3.5 g/h for the 6.67-hour irradiation and 1.8 g/h for the 16.5-hour irradiation. At 1.29 GHz, weight was lost at a rate of 1%/h/100 mW/cm^2. Rectal temperatures decreased slightly during the two exposures to 24-GHz radiation. In contrast, temperatures increased after irradiation with 1.29-GHz microwaves. The maximum increase observed was 5 C during the fifth irradiation at 100 mW/cm^2. During subsequent exposures, the measured increases remained near 2.2 C, but a progressive decrease in preexposure rectal temperature was noticed. Small increases were observed at the lower power densities. One noteworthy result was that, whereas both 2.8- and 1.29-GHz radiation were capable of producing a 2.2 C increase to a critical temperature of 41 C, weakness and agitation were more pronounced at the higher frequency. In general, any effects observed throughout the course of the study were transient, and no residual abnormalities were detected during an extended followup examination.

In a presentation made at the International Microwave Power Institute Symposium in 1976, Guy et al (*@MR0349*) described the complete absence of biologic effects in rabbits following long-term low-level microwave irradiation. The rabbits were placed in a temperature-controlled anechoic chamber with the E-field vector polarized parallel to the long axis of the cage. Exposure to CW 2.45-GHz radiation was for 23 h/d for 6 months at an effective power density of 7 mW/cm^2 at the body axis and 10 mW/cm^2 at the head. The peak SAR for the head was calculated to be 14 W/kg. Periodic examination of the eyes and monitoring of body weight, urine, rectal temperature, hematocrit, hemoglobin, differential count, WBC count, platelet count, and basic blood coagulation capability indicated no significant differences between microwave- and sham-irradiated animals.

After a study of the effects of long-term microwave irradiation on the metabolism of rats, Lovely et al (*@MR2006*), in 1977, reported uniformly negative findings. Sixteen adult male rats were placed for 10 h/night for 13 weeks within a Plexiglas cage inserted into a waveguide. Half of the rats were exposed to CW 918-MHz radiation at an average power density of 2.5 mW/cm^2; the other half were sham irradiated for the entire 910 hours. The calculated SAR averaged 0.9 W/kg. During the course of the experiment, measurements were made of body mass and consumption of food, water, and saccharin solution; serum concentrations of calcium, potassium, sodium, chloride, carbon dioxide, BUN, and glucose; the ion gap; daily colonic temperatures; basal and ether stress-induced corticosterone levels; and behavioral repertoire, consisting of eating, drinking, grooming, activity, and rest. There were no significant differences between the microwave- and sham-irradiated animals. By contrasting their results with previously observed effects at 10 mW/cm^2, Lovely et al proposed the existence of a radiation threshold. Furthermore, they stated that the total dose (fluence or energy density) received was irrelevant in any consideration of microwave-induced biologic effects.

The results of subsequent experiments, reported by Lovely et al (*@MR3087*) at a 1978 symposium, contradicted the earlier results. They found that a 3-month exposure to 2.45-GHz radiation at 500 μW/cm^2 for 7 h/d produced temporary changes in the same biochemical and behavioral variables found to be unaffected by irradiation at 2.5 mW/cm^2. One exception was a lack of change in urinary ketosteroid levels. D'Andrea et al (OP Gandhi, written communication, January 1979) reported no effects on ketosteroid levels, body mass, food and water intake, and motor activity after a 16-week exposure, 5 d/wk, 8 h/d, to 2.45-GHz radiation at 5 mW/cm^2.

In contrast to the uniformly negative findings reported in several of the papers discussed above, Serdiuk (*@MR2518*), in 1969, described various physiologic alterations in rats and rabbits exposed for 180 days to 50-MHz radiation. Irradiation for 10-12 h/d at field strengths of 0.5-6 V/m produced (1) decreases in blood cholinesterase activity, phagocytic activity, and leukocyte and eosinophil counts; (2) an increase in urinary excretion of 17-ketosteroids; and (3) disturbances in conditioned reflex activities and EEG's.

In 1974, Dumanskii and Shandala (*@MR1832*) reported that long-term irradiation (120 days) of rats and rabbits produced significant changes in spontaneous and conditioned reflex activity, EEG, neuroendocrine gland function, blood composition, and tissue morphology. Irradiation was for 8 or 10-12 h/d at power densities as low as 600 pW/cm^2 for CW 50-MHz radiowaves, 0.5 μW/cm^2 for CW 2.50-GHz microwaves, and 1 μW/cm^2 for PW 10-GHz microwaves (pulse width 1 μs, pulse repetition rates 1,000 and 20 pps). Power densities between 1.9 and 10 μW/cm^2 for 50-MHz radiation and between 5 and 10 μW/cm^2 for 2.5-GHz radiation were found to alter motor activity, synchronize cortical rhythms, decrease blood cholinesterase activity and sulfhydryl content, increase secretion of 17-ketosteroids into the urine, increase adrenal gland weight but decrease its ascorbic acid content, and increase uptake of iodine by the thyroid.

Twenty consecutive days of irradiation with 46.2-GHz microwaves for 15 min/d produced changes in immunocompetence, response to infection, and activity of the hypophyseal-adrenal and sympathetic-adrenal systems in mice, according to a 1978 report by Zalyubovskaya and Kiselev (*@MR3066*). Two hundred and fifty animals irradiated at 1 mW/cm^2 were compared with 100 controls. Phagocytic activity and index ($P<0.001$), complement titer ($P<0.05$), and bactericidal activity of the skin ($P<0.01$) decreased to approximately 0.5 of control levels. The concentration of leukocytes ($P<0.05$) decreased to 0.85, and lysozyme titer ($P<0.05$) decreased to 0.25. Microscopic changes occurred in the cells of the thymus, spleen, and lymph nodes, and the weights of these organs decreased. Resistance to an induced infection with Typhus abdominalis declined by 40% following irradiation. Preirradiation decreased the concentration of antibodies to this pathogen by a similar amount. Simultaneous irradiation and immunization with T abdominalis vaccine and tetanus antitoxin (sic) led to increases of 30-40% in mortality and decreases in antibody, lysozyme, and complement titers and in leukocyte concentration. The rate of antibody production and the number of antibody-forming cells in the spleen were lower on the 4th day of immunization in mice irradiated for 10 days than in unirradiated controls.

Examination of the hypophyseal-adrenal system indicated that responses similar to those known to occur during stress and the body's adaptation to stress followed irradiation (*@MR3066*). The concentration of 17-oxycorticosteroids in the blood increased by one-half and that of ascorbic acid in the adrenal cortex decreased by one-third following irradiation. Adrenaline concentrations increased in the blood, hypothalamus, and adrenals, as did the concentrations of noradrenaline, except in the hypothalamus where they decreased. Zalyubovskaya and Kiselev attributed some of the changes observed in immunocompetence to these alterations in the neuroendocrine system.

According to a 1976 report by Moe et al (*@MR2274*), 3 weeks of CW 918-MHz irradiation, 10 h/d at 10 mW/cm^2, were sufficient to alter several behavioral and physiologic variables in rats. A cylindrical waveguide, which provided a uniform electromagnetic field, was placed in an environmentally controlled room that served as the exposure chamber. Reductions of about 20% in food intake and blood glucose and an unspecified reduction in motor activity were observed. No significant differences in body weight, rectal temperature, daily saccharin consumption, or basal and ether stress-induced corticosterone concentrations were noted between the eight control and eight irradiated animals.

(c) Miscellaneous Effects

Nikogosyan (*@MR0106*), in 1967, reported changes in protein fractions of the blood after microwave irradiation of rabbits and rats. Animals were subjected to whole-body irradiation with 3-GHz microwaves at 10 mW/cm^2, 1 h/d for 4-8 months. Decreases in the concentrations of albumin and globulins were noted throughout the exposure period, as were decreases in RNA content of the liver, brain, and spleen. Wangemann and Cleary (*@MR1792*) reported in 1976 that changes in blood chemistry could be induced by irradiation at relatively low power densities. Rabbits were exposed to far-field 2.45-GHz radiation in an anechoic chamber. Both CW and PW (pulse width 10 μs, peak power density 485 mW/cm^2) radiation were used, and each animal was exposed for 2 hours. Statistically significant increases were noted in the levels of glucose, BUN, and uric acid immediately after exposure at 10 and 25 mW/cm^2. After exposure at 5 mW/cm^2, changes were noted in glucose levels but not in BUN or uric acid levels. The concentrations of seven other serum components did not change significantly.

In 1976, Deficis et al (*@MR2171,@MR2190*) noted that serum triglyceride levels in mice were altered following lengthy exposure to microwave radiation. Adult male mice were irradiated 15 h/d for 9 days. The concentration of triglycerides was increased in animals irradiated with 2.4-GHz microwaves at 1.5 and 3.3 mW/cm^2 but remained at control levels for mice irradiated at similar power densities with 2.9-, 5.4-, and 9.4-GHz microwaves. Comparisons with mice exposed to IR radiation at 3.3 mW/cm^2 suggested to Deficis et al that thermal heating was not responsible for the effect, since the triglyceride levels of IR-irradiated mice were similar to those of controls.

Also in 1976, Sparks et al (*@MR1953*) reported irradiating rabbits with 2.45-GHz microwaves at 20-30 mW/cm^2, 4 h/d, 5 d/wk for 8-10 weeks. The animals were irradiated in an anechoic chamber under far-field conditions. Two sets of 16 rabbits were fed an atherogenic diet beginning on the 1st day of microwave radiation exposure. Control animals of similar age and weight were selected from both sets. In a second experiment, rabbits were exposed to RF radiation of 1 MHz at a field strength of 30 V/m. The number of atherosclerotic lesions in the aorta and its cholesterol concentration did not differ significantly between control and irradiated animals.

Pitenin and Subbota (*@MR1904*) reported in 1965 that 10 minutes of localized 2.38-GHz irradiation at 110-160 mW/cm^2 produced ulcers in the epigastric regions of rabbits. Some morphologic changes produced in the viscera of rats by chronic microwave irradiation were discussed by Niepolomski and Smigla (*@MR2469*) in 1966. The rats were irradiated with 10.7-MHz microwaves for 4 h/d for 10 months (values of power density or field strength were not available). Tissue samples from the lungs, hearts, muscles, livers, spleens, kidneys, and brains were taken for microscopic examination. Degeneration was evident in parenchymatous organs, often accompanied by proliferation of endothelial and connective tissue. Inflammatory infiltrations, predominantly of acidophils, occurred near the vascular walls of the parenchymatous organs. Fibrosis and hyalin degeneration were observed in the vascular walls, and scar tissue was found in the heart. The cells and fibers of the CNS showed widespread degenerative effects. Niepolomski and Smigla noted that the morphologic changes resembled those reported to occur with chronic poisoning by metals such as cobalt and lead. Effects specific to microwave irradiation were not discerned.

According to a 1971 report by O'Brien et al (*@MR1164*), irradiation with CW 2.45-GHz microwaves at 140 mW/cm^2 led to extensive necrosis of liver cells in rats and death within 6-8 minutes. Massive hemorrhaging into the abdominal cavity was evident. O'Brien et al stressed the similarity between the results they obtained and those reported by Linke et al (*@MR0239*), in 1962, in rabbits irradiated with a diathermic apparatus operating at similar power densities and frequencies. McLees et al (*@MR1063,@MR1062*), in 1971 and 1972, reported no cellular aberrations in regenerating liver tissue exposed to microwave radiation. Partially hepatectomized rats were irradiated with either continuous or pulsed (pulse width 200 µs, repetition rate 50 pps) 13.12-MHz microwaves. The effective field strength for both conditions was 1,575 V/m, and the calculated SAR was 1.2-1.3 mW/g. Samples of liver tissue were removed at 4-hour intervals between 28 and 44 hours after irradiation had begun. In general, regeneration was found to be unaffected by irradiation.

The metabolism of hepatic, splenic, and thymic cells following microwave irradiation was studied by Miro et al (*@MR1721*). Twenty matched pairs of male mice were used. In each pair, one was irradiated and the second served as a control. The irradiations were performed in an anechoic chamber under far-field conditions. The PW 3.10-MHz radiation had a pulse width of 1 ms, a pulse repetition frequency of 50 pps, and an average power density of 2 mW/cm^2. After 145 hours of continuous irradiation, protein synthesis, as measured by uptake of ^{35}S-methionine, was significantly increased ($P<0.001$) in the spleen, liver, and thymus. Hyperplasia and an increased number of lymphoblasts and reticular cells were evident on microscopic examination of the spleen and thymus.

Faitel'berg-Blank (*@MR0676*), in 1963, described the effects of a 10-minute exposure at 60 W of 41.1-MHz radiation on the absorptive capabilities of the stomachs and intestines of six dogs. Ultrahigh-frequency irradiation induced increases in the average absorption by the intestine and stomach of glucose, water, glycine, and chloride ion. The relative increases were generally smaller for the stomach. Faitel'berg-Blank suggested that a reflex mechanism was responsible and thus that the field exerted its effect primarily on the CNS, which then altered body metabolism.

The gastrointestinal motor activity of rats was reported by Tansy et al (*@MR1432*), in 1971, to be stimulated by an HF electric field. A group of 110 male adult rats was used for two experiments. Each animal was placed for

30 minutes betweeen two condenser plates carrying a 6-MHz electric field with a strength of 15 V/cm; following irradiation, Evan's blue dye was introduced into the stomach. The results indicated that in irradiated animals the stomachs lost and the colons collected significantly (at the 5% confidence level) more dye at 2 and 3 hours postirradiation than did those of control animals. Tansy et al inferred that the quicker gastrointestinal transit time induced by an HF field was due to stimulation of peristaltic muscular activity within the small intestine.

In 1962, Tolgskaya and Gordon (*@MR1933*) described the effects of 3-GHz radiation on neurons associated with skin receptors. Two rabbits and two rats were exposed at 40-100 mW/cm^2 for 30 minutes. A second group of three rabbits and two rats was exposed at 1 mW/cm^2, 1 h/d for 100-200 days. The authors noted that, although this low level of exposure did not increase body temperature, microscopic examination of skin revealed neuronal changes characterized by thickening, distension, and fragmentation.

The growth rate of infantile mice was unaffected by RF irradiation, according to a 1975 report by Stavinoha et al (*@MR1401*). Single 20-minute exposures to 10.5, 19.27, and 26.6-MHz radiation at 5.8 kV/m on the 4th day of life did not alter weight gain during the first 22 days of life. Similarly, multiple (once daily for 5 days) 40-minute exposures to 19-MHz radiation at 8 kV/m and 55 A/m beginning on the 4th day did not alter weight gain during the first 120 days of life.

In an experiment designed to correlate the resistance of an organism to a UHF microwave field with the level of its oxidation-reduction reactions, Koldaev (*@MR0893*), in 1970, compared the lifespans of a total of 70 adult male rats irradiated with 2.38-GHz microwaves at 150 mW/cm^2 under five different experimental conditions. The groups placed in atmospheres of 40 and 10% oxygen 10 minutes prior to irradiation survived 1.4 and 0.72 times as long, respectively, as did the controls (40.1±1 minute). Those given 200 mg/kg S-beta-aminoethylisothiuronium salt or 130 mg/kg cysteamine, substances that inhibit oxidative metabolism, 10 minutes prior to irradiation survived only 0.45 times as long. Koldaev concluded that oxidative processes are important in determining survival during exposure to CW microwave radiation.

Carcinogenicity, Mutagenicity, Teratogenicity, and Effects on Reproduction

(a) Human Studies

No confirmed reports have been found in the literature that describe carcinogenic effects of RF and microwave radiation in humans. A 1976 report by Zaret (*@MR1707*) cited an increased incidence of cancer in two villages in Finland that are located near a Soviet early warning radar system. According to the author, no satisfactory explanation for the increased incidence has been forthcoming. However, because of the circumstantial nature of this situation, it is impossible to associate the increased cancer rate with possible exposure to radar. Puska (*@MR2976*) noted that about 75% of the men in this region smoke, a factor that could possibly contribute to a high incidence of cancer. Furthermore, a study performed by the Finnish Cancer Register failed to detect an abnormal incidence of cancer in Eastern Finland (*@MR3116*).

Some epidemiologic studies have examined possible carcinogenic and reproductive effects of RF and microwave exposure (*@MR1373,@MR0537,@MR0235, @MR3075*). A study described by Sigler et al (*@MR1373*), in 1965, and by Cohen and Lilienfeld (*@MR0537*), in 1970, suggested that an increased percentage of fathers who had been exposed to radar had sired mongoloid children. A subsequent report by Cohen et al (*@MR3024*), in 1977, did not clarify this issue. Lancranjan et al (*@MR0235*), in 1975, described alterations in spermatogenesis in workers exposed to microwave radiation. A recent report by Lilienfeld et al (*@MR3075*), published in 1978, found no evidence for increased incidence of cancer among personnel reportedly exposed to microwaves in the US Embassy in Moscow. These studies are described in more detail in <u>Epidemiologic Studies</u>.

A report by Imrie (*@MR2377*), in 1971, described three cases in which pregnant women were given pelvic shortwave diathermy treatment. The frequency and dose used were not reported; however, shortwave frequencies generally are in the 3-30 MHz range, with 27 MHz being the most commonly used frequency. A 25-year-old patient received a total of nine diathermy treatments 26-61 days after her last menstrual period. She ultimately gave birth to a normal child

2 days before the predicted date. A 27-year-old patient received 11 diathermy treatments 15-43 days after her last menstrual period. Approximately 1 month after her last treatment, she aborted. Products of conception were found on evacuation of the uterus, but no fetus could be identified. In the third case, a 31-year-old patient was given 13 diathermy treatments 19-63 days after her last menstrual period. She ultimately gave birth to a normal child 2 days after the expected date. The author felt that of possible significance was the fact that, in the case of the woman who aborted, irradiation took place close to the day of expected ovulation (and presumably of fertilization), whereas the two women whose pregnancies proceeded normally probably were irradiated after the time of implantation.

Imrie (*@MR2377*) also reported the results of intrauterine temperature measurements of 25 patients before and after treatment with diathermy. A slight rise in temperature was observed; however, the increase was within the normal daily variation in body temperature.

Another case of miscarriage after diathermy treatment was described in 1959 by Rubin and Erdman (*@MR1908*). These authors, however, described other cases in which diathermy treatment apparently had no effect on ovulation, conception, or delivery.

Microwaves have been used to heat the uterine walls of pregnant women during labor, as noted in a 1976 report by Daels (*@MR1606*). Frequency and dose were not specified. No adverse side effects were observed in the 2,000 patients treated in this manner.

A case described by Rosenthal and Beering (*@MR1285*), in 1968, has been associated with reproductive damage due to microwave exposure. A 31-year-old repairman at a weather radar installation had been repeatedly exposed over a 4-year period to microwave emissions at power density levels reported as 30 W/cm^2 or more (frequency not specified). The patient had often performed maintenance on a radar antenna while it was in operation. He occasionally had reported a sensation of warmth while working near the microwave beam. A testicular biopsy revealed a significant decrease in spermatogenesis, and the patient's sperm counts remained low for up to 11 months after his last exposure to microwaves. The biopsy also showed tubular atrophy with focal necrosis and interstitial edema.

Italiano et al (*@MR2615*), in 1976, reported the results of studies of chromosomes from five radar operators, aged 32-52, with work histories of 10-25 years. Four unexposed and clinically healthy individuals served as controls. Approximately 450 metaphases in cultured blood cells were analyzed in each case. No statistically significant difference was found between control and exposed groups in the incidence of chromosomal aberrations.

(b) Animal Studies

Prausnitz and Susskind (*@MR1251*), in 1962, described the effects of prolonged exposure to pulsed 9.27-GHz radiation (500 pps, 2-μs duration) on mice. A group of 200 male Swiss mice was exposed at 100 mW/cm^2 for 4.5 minutes, 5 d/wk for 59 weeks. Animals were irradiated in an anechoic chamber by a horn antenna. Since animals were irradiated in cages (10 animals/cage), distortions in the electromagnetic field may have been produced. A control group of 100 animals was used for comparison. Malignant change in the WBC's (leukemia or leukosis) was found in 21 of 60 irradiated animals (35%) that had died during the experiment. The incidence of this effect in control animals that had died during the experiment was 10% (4 of 40). Lung tumors were also noted, but the incidence was similar for both groups (10-12.5%).

Table III-12 summarizes studies that have reported reproductive changes in animals after exposure to RF and microwave energy.

Bereznitskaya and Kazbekov (*@MR1582*), in 1974, described studies of the sexual systems of male mice exposed to 3-GHz microwaves. A total of 59 male mice in four experimental groups was used in the study. The animals were irradiated for 2 h/d at 10 mW/cm^2. Sexually mature mice in group 1 were exposed for 5 months. Mice from group 2 were irradiated before birth (period of exposure not given), and group 3 mice were irradiated before birth and then for 5 months after they had reached sexual maturity. Mice in group 4 served as

TABLE III-12

REPRODUCTIVE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)	Duration	Remarks	Reference
Mouse (59)	3	10	2 h/d for 5 or more mo	Testicular changes, increase in debilitation and still-births in progeny	Bereznitskaya and Kazbekov (*@MR1582*)
Mouse	1.7	50	30-40 min	Alterations in spermatogenesis	Varma and Traboulay (*@MR0054*)
"	1.7	10	<100 min	Little or no testicular damage	"
"	1.7	10	100 min	Morphologic testicular alterations	"
Mouse (11)	2.45	50	Three 10-min exposures	Increased mutagenicity	Varma et al (*@MR2971*)
Mouse (10)	2.45	100	10 min	"	"
Mouse	3	10	20 min	No significant testicular changes	Varma and Traboulay (*@MR0054*)
Mouse (113 female)	3	10	1 h, 2 x d for 5 mo	Decreased fertility	Bereznitskaya (*@MR0779*)
Mouse, rat (18+)	3.1 (PW)	5-11	7-450 h	No morphologic changes in gonads	Miro et al (*@MR1113*)
Mouse (78)	9.1-9.2	124	Time to elevate temperature 1-6 C for up to 5 d	No significant effect on fertility	Susskind (*@MR1415*)
Mouse (groups of 10)	9.27 (PW)	68-380	2.25-17.75 min	Survivors all sired litters	Prausnitz and Susskind (*@MR1251*)

TABLE III-12 (CONTINUED)

REPRODUCTIVE EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)	Duration	Remarks	Reference
Mouse (200)	9.27 (PW)	100	4.5 min, 5 d/wk for 59 wk	Testicular degeneration in 40% (vs 8% in controls)	Prausnitz and Susskind (*@MR1251*)
Mouse (100)	10	400	5 min	Reversible changes in estrual cycle	Gorodetskaya (*@MR2424*)
Rat (97)	2.45	80 (±10)	10 min or more	Testicular degeneration associated with testicular temperature rise	Muraca et al (*@MR2366*)
Rat (90-120)	24	250	5-15 min	Testicular damage	Gunn et al (*@MR0210*)
Rabbit (8)	3	0.003	80 h over 2-3 mo	Changes in reproductive epithelia	Dolatkowski et al (*@MR2347*)
"	10	0.3	"	No significant reproductive effects	"

controls. Healthy females were mated with mice from each group, and data were collected on various indices of reproductive function. An increase in the incidence of stillbirths was noted in progeny from group 3 mice. An increased incidence of "debilitated" individuals was reported in offspring from groups 1, 2, and 3. Postnatal mortality was also higher in progeny from these three groups, and decreases in average litter size were reported. The testes from 10 mice in each group were examined microscopically. Testicular changes were found in all groups, but more prevalently in the mice from group 3. These changes included tubular atrophy, epithelial desquamation, and giant cell formation.

In 1974, Varma and Traboulay (*@MR0054*) described studies on the testicular effects of microwave irradiation in mice. Male Swiss mice, 56-65 days old, were anesthetized, and each was irradiated 1.2 m in front of a waveguide in an anechoic chamber. The animals were exposed to either 1.7- or 3.0-GHz radiation at 10-200 mW/cm^2 for 10-100 minutes. Immediately after irradiation, the animals were killed; their testes were removed and prepared for microscopic examination. The testes of eight sham-irradiated (anesthetized) mice were used as controls. Exposure to 1.7 GHz at 50 mW/cm^2 for 30-40 minutes resulted in alterations in spermatogenesis. Microscopic observations included depletion of the lumens and disintegration of spermatids, Sertoli cells, and connective tissue surrounding the seminiferous tubules. At 10 mW/cm^2 and 1.7 GHz, little or no testicular damage was observed after exposures of less than 100 minutes. However, exposure to 1.7 GHz at 10 mW/cm^2 for 100 minutes resulted in morphologic alterations, including a reduction in the number of cells in the seminiferous tubules, sloughing of degenerating germinal cells, and changes in the appearance of the lumen. Exposure to 3.0 GHz for 20 minutes at 10 mW/cm^2 caused insignificant testicular damage.

In 1977, Varma et al (*@MR2971*) reported increased mutagenicity in Swiss mice irradiated with 2.45-GHz radiation. The testes of male mice were exposed under one of the following conditions: a single 10-minute exposure at 100 mW/cm^2, three 10-minute exposures at 50 mW/cm^2 in 1 day, and four 10-minute exposures at 50 mW/cm^2 over 2 weeks. These dose levels must be questioned, however, since exposures reportedly occurred in the near field. Following a 24-hour recovery period after irradiation, exposed male mice were mated with unirradiated female mice. Observations of fertility and mutagenicity were made and compared with similar observations in control mice. Male mice were tested by a dominant lethal assay in which a mutagenicity index, proportional to the ratio of early embryonic deaths to the total number of implants, was calculated. The results showed that, although fertility was not impaired in exposed animals, mutagenicity was significantly higher after single and multiple exposures during 1 day. However, the uncertainty associated with an estimation of the number of zygotes formed renders such calculations and conclusions somewhat suspect. No effects were observed after multiple exposures over 2 weeks.

No morphologic changes in the genital organs of mice and rats were found in studies reported by Miro et al (*@MR1113*) in 1965. Animals were exposed to 3.1-GHz pulsed radiation at average power densities of 5-11 mW/cm^2 for up to 450 hours. Short-term exposures at much higher doses resulted in rapid death but did not produce pathologic reproductive changes. Since animals were apparently irradiated in cages, the electromagnetic field may have been distorted.

In a 1958 report, Susskind (*@MR1415*) described studies of the effects of whole-body microwave irradiation on fertility in male mice. A total of 78 fertile mice received single near-lethal doses of radiation (124 mW/cm^2, approximately 9.1-9.2 GHz). The animals were placed in plastic sacks in a vertical position, with their hindlegs spread to expose the genitals. Six groups were irradiated, with each group receiving a different dose. Dose was defined as the amount of irradiation required to raise the rectal temperature to one of six temperatures between 38 and 43 C. Control mice were sham irradiated. Immediately after irradiation, the mice were placed into breeding cages with female mice. The criterion for fertility was the ability to sire a litter of normal size. Most of the irradiated mice sired litters, and no significant difference was found in litter size between control and irradiated mice. Under similar experimental conditions, multiple exposures at 124 mW/cm^2 for 5 consecutive days likewise resulted in no significant radiation effects on fertility in two groups of eight mice each.

Prausnitz and Susskind (*@MR1251*) examined the effects of acute and chronic exposure to pulsed 9.27-GHz radiation (500 pps, 2-μs duration) on testicular function. In the acute study, groups of 10 male Swiss mice were exposed at 68-380 mW/cm^2. The duration of exposure ranged from 2.3 to 17.8 minutes and was sufficient at each power density level to produce 50% mortality. The presence of residual testicular damage was evaluated by breeding surviving males. All survivors sired litters, indicating that sterility had not resulted.

Chronic exposure to microwaves was studied by exposing 200 male mice at 100 mW/cm^2 for 4.5 minutes, 5 d/wk for 59 weeks (*@MR1251*). A control group of 100 animals was used for comparison. Testicular degeneration was found in 23 of 57 (40%) irradiated mice that died during the experiment, whereas the corresponding control group showed an incidence of 8% (3 of 37). The authors noted that rectal temperatures taken periodically in five irradiated mice indicated that each exposure was accompanied by an increase of approximately 3 C during the study.

Gorodetskaya (*@MR2424*) reported in 1964 that a single 5-minute exposure of female mice to 10-GHz radiation at 400 mW/cm^2 resulted in a decrease in the number of sexual cycles per month. The cycle returned to normal within 1 month after irradiation.

Effects of microwave irradiation on the rat testes were described by Muraca et al (*@MR2366*) in a 1976 report. Male albino rats (97) were exposed to 2.45-GHz free-field radiation in such a way that the power density at the scrotum of the rat had a mean value of 80 mW/cm^2 (±10 mW/cm^2). Testicular degeneration was correlated with a rise in intratesticular temperature. For example, a temperature rise to 40 C after a single exposure for 10-73 minutes produced testicular degeneration in 10-30% of the exposed animals. Higher temperature rises resulted in degeneration in a greater percentage of the irradiated animals. Histologically similar testicular effects were observed as a result of water bath submersion at temperatures comparable with those induced by microwave heating. The authors concluded that the most important factor in producing the observed testicular damage was the extent of temperature rise rather than the length of time during which the tissue was at an elevated temperature.

In 1961, Gunn et al (*@MR0210*) described the results of studies designed to measure the effects of 24-GHz radiation on the function and morphology of the rat testis. Three groups of 30-40 rats, 16 weeks old, were anesthetized, and their scrota were exposed at 250 mW/cm^2 7.6 cm from an antenna. Irradiation was carried out under conditions of controlled temperature. The first group of animals received a 5-minute exposure; the second group, a 10-minute exposure; and the third group, a 15-minute exposure. Animals exposed for 5 minutes showed enlarged testes on the 6th day after exposure. Microscopic examination revealed slight to severe edema with some tubular degeneration;

interstitial tissue appeared normal. Focal areas of necrosis and of moderate to severe tubular degeneration were seen in animals exposed for 10 minutes. Animals exposed for 15 minutes had many opaque areas in their testes and also testicular hemorrhages and collapse. Extensive necrosis involving vascular and interstitial tissue was also seen. In general, testicular damage increased in severity with increasing duration of exposure.

Fahim et al (*@MR2294*), in 1975, reported the results of studies in which the testes of rats were exposed to 2.45-GHz radiation from a microwave diathermy unit. Maximum output of the device was 100 W. Animals were anesthetized and exposed at 20 or 100% of maximum power for 1-15 minutes. Increases in testicular temperature were recorded that were directly related to power output and time of exposure. Decreases in fertility and spermatogenesis were found that were correlated with increased testicular temperature.

A Polish study reported in 1963 by Dolatkowski et al (*@MR2347*) involved the long-term irradiation of rabbits under conditions that simulated exposures experienced by radar operators. Male rabbits in two groups were exposed for a total of 80 hours for 2-3 months. Eight animals exposed to 3-GHz radiation (reportedly at 3 $\mu W/cm^2$) near an open microwave transmitter developed changes in the reproductive epithelia of the spermatogenic ducts. However, eight animals exposed near antenna equipment operating at 10 GHz and at a higher power density (300 μW/cm^2) had no significant changes in their reproductive organs. This inverse dose-effect relation over such a wide dose range (factor of 100) makes these results suspect.

Major animal studies that have reported teratogenic RF and microwave effects are summarized in Table III-13.

In a study published in 1975, Rugh et al (*@MR0043*) stated that microwave exposure of pregnant mice to 2.45-GHz radiation produced teratogenic effects at certain dose levels. The same study was discussed by Rugh et al (*@MR1754*) in a 1974 paper. Each animal was exposed in a specially constructed waveguide apparatus under conditions of controlled temperature and humidity. Female mice at the 8th day of pregnancy were used. Although doses were expressed in terms of calories per gram, the incident power density was estimated to be roughly 123 mW/cm^2 (7.37 W forward power), and exposure times varied up to a maximum of 5 minutes. Approximately 855 irradiated litters were examined after termination of pregnancy at 18 days. Various anomalies were observed after accumulation of absorbed doses in the range of 3-8 calories/g. These included exencephaly (herniated brains), hemorrhage, resorption, stunting, and fetal death. The number of litters without anomalous fetuses decreased as the average absorbed dose increased, suggesting a possible dose-effect relationship. Preliminary studies at doses below 2.5-3 calories/g showed no teratogenic effects.

TABLE III-13

TERATOGENIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Mouse (855 irradiated litters)	2.45	123 (estimated) (absorbed doses given)	On d 8 of pregnancy	Possible dose-effect relation on induction of anomalies	Rugh et al (*@MR0043, @MR1754*)
Mouse (77)	3	10	2 h/d on d 1-15 of pregnancy	Increase in fetal death and frequency of developmental deviations, decrease in average fetal weight and level of reflex response	Bereznitskaya and Rysina (*@MR2678*)
Mouse (85)	3	10	1 h, 2 x d for 5 mo	Increase in incidence of stillbirths and postnatal deaths	Bereznitskaya (*@MR0779*)
Mouse (318 litters)	2.45	3.4-28	100 min/d during gestation	Increased incidence of cranioschisis; significant decrease in mean fetal weight (28)	Berman et al (*@MR1583*)
Mouse, rat (55)	3.1 (PW)	5-11	18-306 h	Normal litters, no fetal abnormalities	Miro et al (*@MR1113*)
Rat (30)	0.027	--	--	Placental changes	Moayer (*@MR1117*)
Rat (749)	0.027	55, 70, and 100 W	--	Embryonic abnormalities, increase in embryonic death (dependent on time or irradiation during pregnancy)	Dietzel et al (*@MR0625*), Dietzel (*@MR1826*)
Rat (10)	0.915	10	8 h/d throughout pregnancy (110 h)	No significant effects	Jensh et al (*@MR2574*)

TABLE III-13 (CONTINUED)

TERATOGENIC EFFECTS IN ANIMALS AFTER RADIOFREQUENCY/MICROWAVE EXPOSURE

Species (Number)	Frequency (GHz)	Exposure Conditions (mW/cm^2)*	Duration	Remarks	Reference
Rat	1.7	20-30	45 min-2 h or multiple 20-min exposures	No brain abnormalities, no behavioral effects on progeny	Rioch (*@MR1273*)
"	1.7	10-15	1 h/d or on d 5-8 and 12-16 of pregnancy	Increase in average fetal weight	"
Rat (24)	2.45	10	5 h/d on d 3-19 of pregnancy	Lower relative body weight and brain weight in offspring	Shore et al (*@MR1765*)
Rat	2.45	10 or 40	1 h on d 9 and 16 of pregnancy	No adverse effects in progeny	Michaelson et al (*@MR0362*)
"	2.45	31±3 mW/g (absorbed dose)	20 min during 1 of 7 d of pregnancy	Some increase in fetal resorption, decrease in fetal mass, lower level of brain norepinephrine	Chernovetz et al (*@MR1996*)
"	2.45	100	8-13 min on d 2 or 2 and 5 of pregnancy	Some increase in fetal resorption, decrease in fetal weight (dependent on day of pregnancy)	Laskey et al (*@MR2657*)

*Unless otherwise specified

Embryotoxic microwave effects at a relatively low power density were reported in 1974 by Bereznitskaya and Rysina (*@MR2678*). A total of 77 female white mice was used in the study. Irradiated animals were exposed to 3-GHz radiation at 10 mW/cm^2 for 2 h/d from the 1st to the 15th day of pregnancy. On the 15th day of pregnancy, 21 irradiated mice and 21 control mice were killed and examined. A slight increase in fetal deaths was noted in the offspring of irradiated animals as well as a decrease in the average fetal weight. Average craniocaudal size was also slightly less in fetuses from irradiated mice. Although minor deviations from normal development occurred in the control group, a greater frequency of such deviations was found in the irradiated animals. Hematomas were frequently present in embryos from irradiated females. Certain developmental deviations were found only in the irradiated group. These included apparent hydrocephaly and general embryonic underdevelopment. The average litter size of females allowed to deliver normally was also slightly smaller in the irradiated group than in the control group, and postnatal mortality was greater in offspring of irradiated mice. The behavior of newly born irradiated and control mice in a T-maze was also examined. The desired behavior developed much more rapidly in the control neonates than in the newly born irradiated mice. After a week, the percentage of control mice showing only positive responses in the maze was 2.5 times that of neonates from irradiated dams. The authors concluded that these studies indicated the potential "embryotropic" effects of microwave exposure.

Similar results as well as disturbances in fertility were reported by Bereznitskaya (*@MR0779*) in 1968. This earlier paper had described exposure of sexually mature female mice to 3-GHz pulsed radiation for 5 months both before and during pregnancy. Animals were irradiated twice a day at 10 mW/cm^2 for 1 hour, with a 2-hour break between exposures.

A 1978 report by Berman et al (*@MR1583*) described embryopathic effects in offspring of mice exposed while pregnant to 2.45-GHz radiation, 100 min/d during gestation. Exposures at power densities between 3.4 and 28 mW/cm^2 resulted in no significant increases in rectal temperatures. At the highest power density level, the mean weight of live fetuses in the litter was significantly decreased, and the occurrence of cranioschisis (congenital fissure of the cranium) was found to be significantly higher in the irradiated litters.

In the study of Miro et al (*@MR1113*) mentioned previously, mice and rats exposed to PW 3.1-GHz radiation were examined for possible teratogenic effects. Both male and female animals were irradiated at 5-11 mW/cm^2 (average) for up to 306 hours and then were mated with unirradiated partners. Of those females that became pregnant, all delivered normal litters and no fetal abnormalities were observed.

Moayer (*@MR1117*), in 1971, described placental effects resulting from shortwave irradiation of pregnant rats. A total of 30 pregnant rats was exposed to 27.12-MHz radiation at an undetermined intensity. The progeny were delivered by cesarean section on the 18th day of pregnancy. A total of 91 placentas, 11 from control animals, was examined microscopically. Placental changes noted in the irradiated animals included expansion of the giant cell layer, hydropic degeneration of villi, and ischemia.

Dietzel et al (*@MR0625*), as reported in 1972, abdominally exposed a total of 749 pregnant rats to 27.12-MHz radiation during the first 16 days of pregnancy. Specific exposure times and power levels were not given. Cesarean sections were performed on the 20th day of pregnancy, and a total of 7,800 embryos was examined. Many abnormalities were observed in the embryos examined, but exact numbers were not given. The malformations seen included CNS, abnormalities, eye deformities, cleft palates, and deformities of the tail and extremities. Irradiation on the 1st and 2nd days of pregnancy resulted in death in 65% of the embryos examined, as compared with control rate of 25%. The induction of increased levels of malformation and death occurred only when maternal rectal temperatures reached at least 40 C for 10 minutes. Normally, rectal temperatures of 42 C were reached after 10 minutes of irradiation.

In 1975, Dietzel (*@MR1826*) provided more detail on the results of his 1972 study (*@MR0625*). Three experimental groups were irradiated at RF power levels of 55, 70, and 100 W, respectively. The number of malformations was found to depend on the day of pregnancy on which exposure occurred, irradiation on days 13 and 14 producing the highest proportion of terata.

Jensh et al (*@MR2574*), in a brief 1977 account, described the results of studies on the teratogenic effects of low-level microwave irradiation in rats. Ten pregnant rats were exposed in an anechoic chamber to 915-MHz radiation at 10 mW/cm^2, 8 h/d throughout gestation (total exposure time 110 hours). No increases in body temperature were noted during irradiation. Control animals were placed in the chamber for similar periods without irradiation. All animals were killed on the 22nd day of pregnancy; fetuses were removed, weighed, and prepared for microscopic examination. No significant abnormalities were observed in the litters of the irradiated animals with regard to fetal death, mean fetal mass, deformities, placental weight, litter size, fetal sex ratio, and maternal weight.

Rioch (*@MR1273*), in a 1974 pilot study, described teratogenic studies with hooded and albino rats. Rats of the hooded strain were exposed to 1.7-GHz radiation at 20-30 mW/cm^2 (apparently determined calorimetrically) for 45 minutes to 2 hours or for multiple 20-minute exposures. The brains of irradiated fetuses were compared with those from control fetuses. No abnormalities were found, and no behavioral differences were observed between the young from irradiated and those from control rats. In another series of experiments, albino rats were subjected to 1.7-GHz radiation at 10-15 mW/cm^2, for 1 h/d, on the 5th-8th and 12th-16th days of pregnancy. The average fetal weight of irradiated litters was found to be greater than that of the control group.

Data reported by Shore et al (*@MR1765*) in 1977 suggested that exposure of pregnant rats to 2.45-GHz radiation at 10 mW/cm^2 affected body and brain weight in offspring. Animals were exposed for 5 h/d either parallel to the E-field vector or parallel to the H-field vector from day 3 to day 19 of gestation. Results indicated that relative body weight and relative brain weight were lower in the offspring of exposed animals, with the greatest effect seen in animals exposed parallel to the E-vector (when optimum coupling occurs between RF/microwave energy and animals).

Michaelson et al (*@MR0362*), in 1976, briefly described results of experiments in which pregnant rats were exposed to 2.45-GHz radiation for 1 hour on the 9th and 16th days of gestation. Power densities reportedly were 10 and 40 mW/cm^2. No adverse effects were observed in the dams or in their progeny. No change in duration of gestation or litter size was observed in relation to sham-irradiated dams, and no changes were seen in growth and development of progeny.

In 1977, Chernovetz et al (*@MR1996*) reported the results of studies in which pregnant rats were exposed to microwave irradiation at 2.45 GHz. The animals were subjected to 20 minutes of irradiation at an absorbed dose rate of 31±3 mW/g (determined calorimetrically; average whole-body dose about 37 J/g) in a multimode cavity. Exposures occurred during 1 of 7 days of gestation, the 10th through the 16th. Control groups of pregnant rats were sham irradiated. On the 19th day of gestation, 35 irradiated rats and 19 control rats were given a drug overdose, and deliveries were made by cesarean section. No gross structural abnormalities were observed in the offspring. However, signs of heat stress, such as hemorrhage and edema, were noted in the irradiated animals. The percentage of resorbed fetuses was higher in the irradiated group (13.5%) than in the control group (1.8%). Average fetal mass was also lower in the irradiated group. The brains were removed from 20 irradiated fetuses and 20 control fetuses, and whole-brain levels of norepinephrine and dopamine were determined. The average level of norepinephrine was found to be lower in the brains of microwave-irradiated fetuses than in the brains of control fetuses. Dopamine levels did not differ significantly.

In a 1970 preliminary report, Laskey et al (*@MR2657*) presented the findings of a pilot study in which pregnant rats were irradiated at 2.45 GHz. Animals were exposed for 8-13 minutes at 100 mW/cm^2 ±15% (as measured in the absence of the target) on day 2 or on days 2 and 5 of pregnancy (preimplantation), on day 8 of pregnancy (postimplantation), or on day 13 (postorganogenesis). On day 19 of gestation, all animals, including controls and sham-irradiated rats, were killed. Postexposure increases in mean rectal temperature were noted in the irradiated groups. Fetal resorption reportedly was significantly increased in the preimplantation group, but this was not supported by the data given. Litter size was not significantly less in the irradiated animals. However, the mean fetal weights in the postimplantation and postorganogenesis groups were below those in the preimplantation group.

In 1975, Krueger et al (*@MR2399*) described the effects of electromagnetic radiation on the reproductive capacity of chickens. Young hens were exposed in metal wire cages to radiation at various frequencies and power densities for 12 weeks (exact exposure times not specified). Animals were irradiated in cages, and the doses reported were corrected for metallic reflection of the incident radiation by the cages. Young hens exposed to either 260-MHz (0.005-0.125 mW/cm^2), 915-MHz (0.25-1.0 mW/cm^2), or 2.44-GHz (1.0 mW/cm^2) radiation showed immediate decreases in egg production rate. Exposures of both hens and cocks did not result in any decreases in fertility or increases in embryonic abnormalities.

Van Ummersen (*@MR1654*), in 1961, reported the results of studies of the effects of 2.45-GHz radiation on developing chick embryos. A total of 507 eggs was used, of which 366 were irradiated, 109 served as controls, and 32 were not fertile. Eggs were exposed at the 48-hour stage of development to radiation from a dipole antenna in a temperature-controlled anechoic chamber. Exposure levels were 200-400 mW/cm^2 for 1-15 minutes. After irradiation, the eggs were allowed to develop for another 48 hours, after which the embryos were removed and examined.

Irradiation of eggs at 400 mW/cm^2 produced a dose-related increase in mortality; exposure for approximately 5-5.5 minutes was required to produce at least 50% mortality (*@MR1654*). Similar effects were noted at 280 and 200 mW/cm^2, with exposures of 8.5-9 and 14-15 minutes, respectively, being required. Surviving embryos exposed at a level producing mortality had a high incidence of abnormalities that generally fell into two categories. The first type included gross abnormalities that were not restricted to any specific region of the embryo. These abnormalities appeared to be the result of a general inhibitory effect on growth and differentiation and typically included such effects as swollen body size, lack of brain differentiation, and suppression of development of cardiac compartmentalization. The second type of abnormality included inhibitory effects seen only in the posterior region of the embryo. The temperature in all embryos in which effects were observed reached at least 55 C. The author suggested that thermal effects may have been responsible for the observed abnormalities and deaths, but that other factors, acting either concomitantly or synergistically with hyperthermia, could not be ruled out.

In 1975, Hamrick and McRee (*@MR0350*) reported exposing Japanese quail embryos to 2.45-GHz radiation. Fertilized eggs were placed in a Styrofoam holder 60 cm from a horn irradiator in an anechoic chamber. Batches of 19 eggs were exposed at 30 mW/cm^2; at that dose level, the temperature within the eggs ranged from 32 to 38 C. Eight 24-hour exposures of each batch were made, with each exposure beginning 24 hours after the start of incubation. The incubation period was 16-17 days. A total of 110 exposed quail and 102 control quail was killed and examined 24-36 hours after hatching. Examination of blood samples revealed no significant changes except for a slight lowering of hemoglobin level. No gross abnormalities were seen.

In a similar 1975 report, McRee et al (*@MR0032*) described experiments in which quail eggs were exposed to 2.45-GHz radiation for 4 h/d during the first 5 days of incubation. Three series of 19 fertilized eggs each were irradiated at a far-field power density of 30 mW/cm^2. Quail were weighed, killed, and examined for malformations 2 days after hatching had begun. No significant differences were observed relative to controls in body weight and blood characteristics, and no gross malformations were observed in irradiated quail.

Carpenter and Livstone (*@MR0502*), in 1971, reported the abnormal development of insect pupae induced by microwave irradiation. Pupae of the beetle *Tenebrio molitor*, in the 2nd or 3rd day of pupation, were exposed to 10.155-GHz radiation in a section of a waveguide. Of 137 control pupae, 122 developed into normal adults. Forty of 44 pupae placed in a nonpowered waveguide as additional controls developed normally. Exposure of pupae at 20-80 mW power for 20-120 minutes produced a dose-related incidence of death and abnormalities. The abnormalities observed involved various degrees of wing malformation. Experiments designed to duplicate temperature increases induced in the pupae during irradiation suggested that the changes observed could not be explained as thermal effects.

A 1978 paper by Pay et al (*@MR3120*) compared the effects of microwave irradiation and conventional heating on egg production in *Drosophila melanogaster*. Egg production in both cases was significantly reduced. However, subsequent survival of eggs laid by microwave-irradiated (2.45 GHz, 10 minutes, 0.644 W/g) females was significantly lower than survival of eggs laid by heat-exposed females. The authors concluded that the two treatments did not produce results consistent with identical mechanisms of action, even though heating may have been involved in each case.

Reports of mutations resulting from microwave irradiation have been generally limited to plants. For example, Harte (*@MR2680*), in 1973, described the production of morphologic mosaic plants in the second generation of Oenothera hookeri after treatment of pollen and plants with radiowaves. Similar mutagenic results were reported by Harte (*@MR2589*) in 1975 after irradiation of the pollen of Antirrhinum majus with 200-MHz radiowaves.

Blackman et al (*@MR2963*), in a 1977 report, described experiments designed to determine the effect of microwave exposure on mutation induction in bacteria. Log phase cultures were irradiated in culture dishes for 3-4 hours at 35 C; the bacteria were exposed either at 2.45 GHz and 10 or 50 mW/cm^2 (far field) or at 1.7 GHz and 88 V/m (near field). No mutagenic activity could be detected under any of the conditions used.

The effects of microwaves on mammalian chromosomes were studied by Janes et al (*@MR1016*) and described in 1969. Unanesthetized male Chinese hamsters were exposed to 2.45-GHz radiation from an open microwave oven. The oven was alternately on for 3 minutes and off for 1 minute for a total exposure of 12 minutes within a 15-minute period. The animals were irradiated individually in a perforated plastic cylinder placed horizontally 50 cm in front of the oven, with the axis of the cylinder parallel to the front of the oven. Power density measurements were not available because the exposures were not made under far-field conditions. Animals were irradiated either 15 minutes before, 15 minutes after, or 2 hours after injection of a 0.1% solution of Colcemid, which is used to arrest dividing cells at the metaphase stage. Sham-irradiated control animals were similarly injected. Five hours after irradiation, the animals were killed by an injection of sodium pentobarbital. Bone marrow cells were then removed, fixed, and examined for mitotic and chromosomal aberrations. Chromosomes from irradiated animals did not show an increased incidence of aberrations; however, an increase in chromosomal "stickiness" was noted in the preparations from irradiated animals.

Lymphocytic chromosomes from microwave-irradiated Chinese hamsters were examined in a study described by Huang et al (*@MR1663*) in 1977. Three-month-old male hamsters were individually placed in polycarbonate containers and exposed to 2.45-GHz radiation, 15 min/d, for 5 consecutive days at 5, 15, 30, or 45 mW/cm^2. Animals were irradiated in groups of five under far-field conditions and in a chamber with controlled temperature and humidity. Control animals were sham irradiated. The highest power density produced a 1.6 C increase in rectal temperature. Immediately after the last exposure, animals were bled and cultures of blood cells were prepared. Similarly, bone marrow cells were taken and cultured immediately after irradiation. After a specified time, colchicine was added to the cultures to arrest mitosis. Cells were then harvested and prepared for microscopic examination. No significant increases in chromosomal aberrations were seen in cells from irradiated animals. However, cells from the peripheral blood of animals irradiated with 5-45 mW/cm^2 showed a dose-dependent reduction in the number of mitogen-stimulated lymphocytes undergoing mitosis. Autoradiography of radioactively labeled cells showed no evidence of any alteration in repair of DNA.

Heller and Teixeira-Pinto (*@MR0987*) reported in 1959 that chromosomal aberrations could be produced in garlic root tips by pulsed 27-MHz radiation. In 1970, Heller (*@MR0988*) elaborated on this effect and described similar results from experiments with cultured mammalian cells and plant cells. The experiments involved irradiating cultured human lymphocytes and cultured Chinese hamster lung cells with unspecified doses of pulsed 21-MHz radiation (100 pps, 10 μs) for 30 minutes. Temperature was controlled at 27 C. Chromosomal damage was reported to be significantly higher in irradiated cells than in control cells. Such damage included single chromatid breaks, dicentric chromosomes, and occasional erosion of all chromosomes within a cell. These results are difficult to evaluate, however, because of the lack of experimental detail and dosimetric information. In other experiments discussed by the author, exposure of male germ cells of Drosophila to pulsed 20- to 30-MHz radiation reportedly produced visible mutations as well as an increase in the frequency of "crossing over" events. However, once again, experimental details were not given, and the significance of these studies is not clear.

Other reports of in vitro microwave-induced chromosomal damage were made by Mickey and Koerting (*@MR0156*) in 1970. Cultures of Chinese hamster lung cells were placed in a capacitor gap 12 mm in width. Cultures were irradiated for 30 minutes at 15, 19, 21, and 25 MHz (pulsed radiation, 100 pps, 50 μs). The dose was calculated by the authors to be about 50 mW/cm^2. Fourteen experiments were performed and involved an analysis of 12,463 cells, including controls. Each treated culture was matched with a sham-irradiated control culture. Cultures in these experiments were incubated at 37 C. It was not clear, however, whether temperature was controlled during the actual 30-minute exposure. Cells exposed to 19- or 21-MHz radiation showed significant numbers of chromosome breaks, especially during the first division after treatment. Few breaks appeared immediately after exposure, and cells irradiated with 15 MHz showed no observable breaks.

In a 1975 report by Mickey et al (*@MR0121*), similar results were described. Cultured hamster lung cells showed increased numbers of chromosome breaks after irradiation at PW 21, 25, and 40 MHz (100 pps, 50 μs). In vivo exposure to frequencies of PW 20-35 MHz (1,000 pps, 77 μs) for 18-57 hours resulted in increases in abnormal mitoses in bone marrow cells and increased meioses in testicular cells. Both in vivo and in vitro irradiation at 10-500 mW/cm^2 and 9.3-9.4 GHz produced increases in chromosome breaks. However, comparable exposure at 23-24 GHz failed to show these effects. Detailed dose information was not given.

The in vitro production of chromosomal aberrations in animal and human cells has also been described in a 1974 report by Chen et al (*@MR0013*). Cells were placed in an open-ended waveguide and exposed to 2.45-GHz radiation at various intensities. Conventional heating of nonirradiated cells to 45 C failed to produce comparable levels of chromosome changes.

Some studies have investigated the effects of microwaves on DNA. Varma and Traboulay (*@MR1790*), in 1977, described the isolation of testicular DNA from mice after exposure to 1.7-GHz radiation. The animals were anesthetized before exposure, and only the testes were irradiated. The exposure time was 30 minutes at 50 mW/cm^2. Rectal temperatures after exposure increased 1-2 C. Thermal profiles of the irradiated DNA sample were interpreted as suggesting strand separation. In 1966, however, Takashima (*@MR1426*) reported that irradiation of solutions of DNA in the frequency range of 1-10 MHz did not produce strand separation or a change in viscosity.

Additional studies of the effect of microwave radiation on DNA in solution were described by Hamrick (*@MR1024*) in 1973. Thermal denaturation curves of DNA solutions exposed to 2.45-GHz radiation at 94 mW/cm^2 were compared with control curves. No differences could be detected.

Epidemiologic Studies

A number of epidemiologic studies have been conducted on populations exposed to RF and microwave radiation. Much of this work has been performed during the last 25 years by Russian and Eastern European investigators. Those reports discussed here are generally representative of the types of findings presented. Many of these investigations have been designed to detect the production of ocular effects, but studies have also dealt with cardiovascular, hematologic, neuroendocrine, CNS, and fertility effects. Unfortunately, a number of deficiencies exist in many of the studies reported here. The most common problems are (1) failure to quantify the degree of RF/microwave exposure, (2) comparison of dissimilar exposed and control populations, particularly with respect to age, (3) lack of description of diagnostic criteria used, and (4) analysis of data in terms of independent groups rather than in terms of matched pairs. Table III-14 summarizes the major articles discussed in this section.

Robinette and Silverman (*@MR3058*), in 1977, described some of the findings of a 2.5-year study of approximately 40,000 male technicians in the US Navy. Approximately 50% of the subjects were considered to have been "occupationally exposed" to microwave radiation; the other men served as controls. Little information was given in this report on the method of determining whether an individual was occupationally exposed. Assignment to a group was based on the type of work done by the men and on a discussion with

TABLE III-14

EPIDEMIOLOGIC STUDIES OF PERSONS EXPOSED TO RADIOFREQUENCY/MICROWAVE RADIATION

Number: Exposed	Number: Control	Frequency (GHz)	Exposure Conditions*	Exposure Duration	Authors' Findings	Reference
507	--	--	0.2-6 mW/cm^2	1-10 or more yr	No statistically significant correlation between exposure and various adverse effects	Czerski et al (*@MR0015*), Siekierzynski et al (*@MR0046,@MR0047*)
19,965	20,726	--	Naval electronic technicians	--	No significant differences in mortality	Robinette and Silverman (*@MR3058*)
736	559	--	Military personnel	--	No ocular anomalies noted up to 1 yr postirradiation, minor changes evident at 3 yr	Zaret et al (*@MR1517*), Eisenbud (*@MR0653*), Cleary and Pasternack (*@MR0180*)
40	4,560	--	Radar workers admitted to VA hospitals	--	Decrease in risk of cataract production	Cleary et al (*@MR0182*)
102	100	0.6-10.7	--	4 or more yr	Statistically significant increase in lens opacities	Majewska (*@MR0248*)
600	300	"UHF"	--	--	No significant ocular effects	Kheifets (*@MR2385*)
91	135	--	Military personnel	--	"	Appleton and McCrossan (*@MR0166*)
605	493	--	Air Force personnel	--	Possible trend in older age groups with respect to occurrence of opacities in exposed subjects	Appleton (*@MR0154*)
377	320	--	Military personnel	--	No significant ocular differences except higher incidence of ocular effects in exposed subjects with family histories of visually related medical conditions	Odland et al (*@MR0270*)

TABLE III-14 (CONTINUED)

EPIDEMIOLOGIC STUDIES OF PERSONS EXPOSED TO RADIOFREQUENCY/MICROWAVE RADIATION

Number Exposed	Number Control	Frequency (GHz)	Exposure Conditions*	Exposure Duration	Authors' Findings	Reference
507	--	--	0.2-6 mW/cm^2	--	No correlation between lens translucency and exposure	Siekierzynski et al (*@MR0046*)
68	30	"Radar"	--	--	Higher incidence of opacities in exposed subjects	Tengroth and Aurell (*@MR0005*), Aurell and Tengroth (*@MR1928*)
705	--	--	--	--	No lenticular or retinal effects	Hathaway et al (*@MR0020*)
1,000	2,000	--	<0.1 mW/cm^2, 0.1-1 mW/cm^2	4 h/d for 1-15 yr	Incidence of opacities statistically correlated with exposure	Zydecki (*@MR1799*)
1,180	200	--	Less than "several hundredths of a mW/cm^2" up to "a few mW/cm^2"	5-15 yr	Increased fatigue, irritability, cardiac pain, bradycardia	Sadchikova (*@MR1757*)
34	--	--	--	--	Cardiac and circulatory disorders	Monayenkova and Sadchikova (*@MR1118*)
100	--	"SHF"	--	--	Autonomic and cardiovascular disorders, weakness, cerebrovascular and coronary vascular spasms, changes in ECG	Drogichina et al (*@MR0634*)
105	--	30	"Several mW/cm^2"	5 yr	Cardiovascular disorders, weakness, headaches, insomnia, hypertension	Glotova and Sadchikova (*@MR0084*)
100	100	"Radar"	"Several mW/cm^2" or less	1-10 yr	Weakness; ECG, autonomic, and vascular changes	Sadchikova and Nikonova (*@MR0287*)
115	100	"	"Several hundred parts of a μW/cm^2"	"	"	"

TABLE III-14 (CONTINUED)

EPIDEMIOLOGIC STUDIES OF PERSONS EXPOSED TO RADIOFREQUENCY/MICROWAVE RADIATION

Number		Frequency (GHz)	Exposure Conditions*	Exposure Duration	Authors' Findings	Reference
Exposed	Control					
80	80	"SHF"	10 mW/cm^2	7 h/d	Abnormal ECG, changes in blood lipid indices, hypertensive disease, coronary insufficiency	Medvedev (*@MR1081*)
334	--	--	<0.2 mW/cm^2	--	"	"
477	340	--	--	--	Retrospective--no ocular effects noted	Shacklett et al (*@MR0294*)
50	50	"Metric range"	45-160 V/m	3-5 yr	Increase in incidence of functional nervous system disorders in proportion to length of exposure; cardiovascular, gastrointestinal, lenticular, and neuroendocrine changes noted	Kleyner et al (*@MR0873*)
30	--	"UHF"	10-170 μW/cm^2, occasional exposure to 500 μW/cm^2	6-7 x mo for 5-15 yr	Cardiovascular and neuroendocrine changes	Fofanov (*@MR0079,@MR0691*)
226	88	2.88, 9.375	3.9-31 mW/cm^2	--	Increase in capillary fragility and WBC, decrease in RBC	Barron et al (*@MR0856,@MR0857*)
335	--	0.4-9	Aircraft workers	Intermittent	No significant change in RBC, WBC, platelet count	Barron and Baraff (*@MR0170*), see also Barron et al (*@MR0856,@MR0857*)
100	--	"SHF"	Generally <10 μW/cm^2	--	Weakness; circulatory, neuroendocrine, and WBC changes	Gembitskiy et al (*@MR0739*)
131	800	--	"Several" mW/cm^2	5-10 yr or more	Some decrease in thrombocytes and leukocytes	Sokolov et al (*@MR2667*)
18	12	0.002-0.02	5-20 kW output	--	No significant changes in blood pressure, pulse rate, attention span; monocytosis	Stefanov et al (*@MR1405*)

TABLE III-14 (CONTINUED)

EPIDEMIOLOGIC STUDIES OF PERSONS EXPOSED TO RADIOFREQUENCY/MICROWAVE RADIATION

Number Exposed	Number Control	Frequency (GHz)	Exposure Conditions*	Exposure Duration	Authors' Findings	Reference
20	12	(1) 2.9 (PW) (2) 3.6-4.0 (3) 0.194-0.200	(1) 40 W output (2) 7 W output (3) 150-600 W output	--	Same as above plus leukopenia	Stefanov et al (*@MR1405*)
--	--	--	--	Up to 10 yr	Decrease in platelets; some lymphocytosis, eosinophilia	Baranski and Czerski (*@MR0850*)
54	--	"RF"	More than 20 V/m	--	Decrease in phagocytic activity	Volkova and Fukalova (*@MR2673*)
38	--	30	--	3.5 h/d	Changes in thyroid function	D'yachenko (*@MR1835*)
72	30	30-300	1 mW/cm^2 or less	Up to 10 yr	Decreased leukocytes and erythrocytes; increased concentration of microbial flora in oral cavity; decreased phagocytic activity; increased lymphocytes; subjective complaints	Zalyubovskaya and Kiselev (*@MR3066*)
162	--	3-30	--	--	Headache, fatigue, irritability, disturbances in EEG and blood chemistry	Klimkova-Deutschova (*@MR1866*)
120	--	"High-frequency"	--	--	Subjective symptoms and flattening of EEG correlated with length of exposure	Baranski and Edelwejn (*@MR0006*), Edelwejn and Haduch (*@MR1836*)
25	407	--	Personnel exposed to radar	--	Greater percentage of fathers of mongoloid children had been exposed to radar	Sigler et al (*@MR1373*), Cohen and Lilienfeld (*@MR0537*), see also Cohen et al (*@MR3024*)
31	30	3.6-10	"Tens to hundreds" of $microwatts/cm^2$	--	Decreased spermatogenesis	Lancranjan et al (*@MR0235*)

*Values given in quotes are as translated from original article.

the Navy as to which job classifications offered the greatest potential for exposure to microwave radiation. No quantitation of exposure was available, and the two groups were not matched.

Military service and Veterans' Administration records, which included data on mortality, morbidity, and requests for disability compensation, were used in the study (*@MR3058*). Statistical tests showed a small but significant increase in the incidence of accidental mortality. The authors felt that this may have been due to an excessive number of deaths in aircraft accidents in the exposed group, possibly resulting from the fact that a larger proportion of the individuals in this group had become flying officers. Data on disease mortality showed that in each category the number of deaths observed in each group was less than would have been expected in the general population. In the exposed group, increases in mortality from malignant neoplasms, stroke, chronic nephritis, influenza, pneumonia, and cirrhosis were found not to be statistically significant.

Czerski et al (*@MR0015*) and Siekierzynski et al (*@MR0046,@MR0047*), in 1974, reported the results of a series of retrospective epidemiologic studies that attempted to find relationships between exposure to microwave radiation and the incidence of adverse effects (neurotic syndromes, gastrointestinal tract disturbances, cardiocirculatory disturbances, lenticular opacities). A group of 507 workers had been exposed at average power densities of 0.2 mW/cm^2, with momentary exposure to 6 mW/cm^2. A second group of 334 workers had been exposed at power densities below 0.2 mW/cm^2. The workers were exposed for various periods of time, and individuals from each group worked under identical conditions except for the level of exposure to microwave energy. Adverse medical findings were statistically analyzed with regard to duration of exposure (1-5, 6-10, 10 or more years) and age of subject (20-25, 26-30, 31-35, 36-45 years). Data from a nonexposed control group were not used for comparison; the authors stated that a comparable group of control subjects meeting all requirements for matching could not be found. No statistically significant correlation was found between the variables studied, and the authors concluded that exposure at power densities in the 0.2-6 mW/cm^2 range appeared to be as safe as exposure below the 0.2 mW/cm^2 level.

In their study of lens translucency in workers exposed to microwaves, Siekierzynski et al (*@MR0046*) performed detailed ophthalmic examinations with a slit lamp. The translucency of the lens was graded according to five classification criteria. A description of standardized diagnostic criteria used for the classification scheme was not presented. One of the coauthors carried out or supervised all examinations to ensure uniform evaluation of lens translucency. Statistical analysis did not reveal any association of lens translucency with the amount of exposure to microwave radiation; however, a negative association was found between lens translucency and age.

Zaret et al (*@MR1517*), in 1963, presented a study of ocular anomalies in a sample of workers exposed to microwave radiation. The study sample was selected from 13 separate installations involving a wide variety of microwave operations including research, development, operation, installation, maintenance, and testing of microwave equipment (particularly radar). The microwave radiation at these installations was limited to power densities near 10 mW/cm^2, with possible short-term exposures at higher power densities. The final sample comprised 736 microwave workers and 559 control individuals. The ophthalmic examinations included pertinent visual history, visual acuity tests, and slit lamp examination and stereophotography of the lens. A means of measuring and scoring ocular defects was discussed. The analysis was based on various ophthalmic indices, including posterior polar defects, minute defects, opacification, relucency, and sutural defects. Statistically significant differences were found between exposed and control groups for posterior polar defects and opacities, but the authors concluded that, overall, the differences were clinically insignificant and that the extent of minor lenticular imperfection was not a clinically useful indicator of cumulative exposure to microwave radiation. Two complicating factors in the study were noted. The first was the possibility that some workers may have been exposed to ionizing radiation as well as to microwave radiation. The second was lack of a standard method of lens examination and the lack of a uniform method of recording the results of the examinations.

In 1964, Eisenbud (*@MR0653*), presented a refined statistical analysis of the earlier data of Zaret et al (*@MR1517*). His analysis also included a retrospective study of cataract cases in veterans of World War II and the Korean War. The subjects of the study were military personnel who used microwave equipment and personnel who had been engaged in military radar work during World War II and the Korean War. Eisenbud's study used primarily linear regression and multivariate analysis of variance techniques. Findings revealed an apparent increase in the incidence of defects in the lenses of radar workers. Eisenbud noted a significant statistical correlation between microwave exposure and an increased incidence of lens defects and a general lack of evidence to support alternate explanations. However, the types of lens defects that were correlated with exposure to microwaves were such that they did not interfere with vision, and their significance or association with the development of cataracts is unknown.

Another analysis of the same data (*@MR1517,@MR0653*) was published in 1966 by Cleary and Pasternack (*@MR0180*). The following findings were reported: (1) Individuals engaged in radar work had greater numbers of minor lens changes than did controls, (2) posterior polar defects and opacification accounted for the significant differences in ocular anomalies, and (3) the relationship of environmental exposure factors to lens changes was significant for all exposure variables ($P<0.05$), including duration of employment involving microwave exposure.

Cleary et al (*@MR0182*) presented a report in 1965 of an epidemiologic survey of cataract incidence in radar workers employed by the military. The study used medical records of Army and Air Force veterans of World War II and the Korean War. The diagnostic indices of all hospitals in the Veterans' Administration system were screened to select a sample of 2,946 white male veterans born after 1910 who had been treated for cataracts between 1950 and 1962. Controls (n=2,164) were selected from the same sources by using adjacent hospital register numbers. The lower limit on year of birth (1911) minimized dilution of the sample with expected senile cataracts. The military records of each veteran were abstracted to determine military occupational specialties and to enable categorization of the sample population as either radar or nonradar workers.

Analysis of the data indicated that a larger proportion of veterans without cataracts had been radar workers than had those with cataracts (*@MR0182*). Significant differences in risk were obtained when the sample was partitioned by branch of service, but numbers of personnel were too small to make definitive statements (P>0.1). When the data set was analyzed by age, no differences were observed in age-specific cataract incidence between the men who had been exposed to microwave radiation and those not exposed. The usefulness of the results of this study was limited by several factors, including the small number of military personnel in the sample having radar-related occupations, the difficulty of defining occupation on retrospective surveys, and the lack of estimation of possible bias due to variability of hospital utilization rates among the different occupational groupings.

Majewska (*@MR0248*), in 1968, studied 200 workers employed for from 6 months to 12 years at installations generating high-intensity microwaves in the frequency range of 600 MHz - 10.7 GHz. Also examined were 200 age-matched controls not exposed to radiation in this frequency range. Lenses were examined with an ophthalmoscope and a slit lamp after dilation of the subjects' pupils. Lens changes were detected in the eyes of 168 of the subjects and of

148 of the controls. This difference in incidences was calculated to be statistically significant. The effects of long-term exposure were examined by comparing 102 employees who had worked with HF electromagnetic wave generators for over 4 years with 100 age-matched controls. Members of both groups were graded 1 through 5 on the degree of lens opacity detected. Majewska concluded that the mean grade of opacities in the exposed workers was greater than that in the controls. The changes in grade in exposed workers increased out of proportion to their age, on the basis of the experience in the age-matched controls. Results were summarized as suggesting a potential harmful effect of microwaves, even at intensities allowed by safety regulations (intensities not specified) when exposure was sufficiently long (4-5 years).

Some limitations of this study (*@MR0248*) were that sample selection criteria were not stated and that no information was given as to whether the examining ophthalmologists knew if subjects examined were exposed individuals or were controls.

A 1970 report by Kheifets (*@MR2385*) described a study conducted over a period of 4 years, during which workers exposed to "UHF" devices were examined for ocular anomalies. A total of 600 subjects was evaluated on the basis of their exposure to "non-thermal" intensities of radiation reported to be in the decimeter, centimeter, and millimeter range (which would correspond approximately to 300 MHz - 300 GHz). A control group of 300 age-matched subjects included individuals who were not known to have been exposed to electromagnetic fields in this frequency range. Routine ophthalmic examinations of individuals from both groups revealed no significant differences in the state of the crystalline lens between the two groups. However, a specific type of clouding of lens tissue that was not observed in control subjects was found in six subjects (1%) in the experimental group.

Appleton and McCrossan (*@MR0166*), in 1972, reported the results of a clinical survey conducted to determine the effects of microwave exposure on the eye. The sample population consisted of 226 military personnel who were examined semiannually between November 1968 and May 1971. Microwave-exposed workers were defined as those who worked around Signal Corps electronic communication, detection, guidance, and weather equipment. Such equipment emits large amounts of microwave radiation, and the investigators felt that personnel exposed to this type of radiation may have been exposed to the highest intensities of microwaves encountered in this country. However, no specific quantification of microwave exposure or frequencies was made. Selection of personnel for inclusion in the study was based on the military post's Occupational Vision Program. Individuals with a history of working directly with microwave-emitting equipment were used as subjects (n=91), and those who denied any exposure were used as controls (n=135). No formalized sampling procedure was documented. Diagnoses were based on slit lamp examination of dilated pupils by ophthalmologists. The examiners noted presence or absence of opacities, vacuoles, and posterior subcapsular iridescence. No difference in the occurrence of ocular anomalies was detected between the exposed and the control groups.

In 1973, Appleton (*@MR0154*) reported the results of an extended survey of military personnel at seven installations. Included were the subjects discussed in the preceding paper (*@MR0166*). Those military personnel who were considered likely to have been exposed to microwaves at each location were compared with control personnel considered unlikely to have been exposed. Trained ophthalmologists examined the subjects for lens opacities, vacuoles, and posterior subcapsular iridescence. The populations were screened by the same team of ophthalmologists at each location except one. The tests were set up so that examining ophthalmologists did not know which population, exposed workers or controls, an examinee was from. Controls were selected to be as similar as possible to exposed workers with respect to age and sex variables. The overall analysis compared the numbers of the three lens anomalies in the exposed workers and the controls in different age categories.

The results indicated the existence of a trend in older age groups, particularly in persons over 60 years old, toward a greater incidence of opacities among exposed personnel (*@MR0154*). However, the small number of subjects in many age categories (sometimes less than six) makes this conclusion uncertain. In an analysis of pooled data, similar signs of possible effects of microwave radiation were observed in both exposed workers and controls. The level of statistical analysis in this study was not optimal. Matched-pair analytical techniques were not implemented to control for confounding variables, and the more sophisticated statistical techniques were not employed. A lack of quantitation of extent of exposure to microwaves further limited the value of the results from the study.

A 1973 study by Odland (*@MR0270*) examined the relation of microwave exposure to the development of several ocular anomalies in personnel from eight military installations. The study population consisted of 377 individuals occupationally exposed to microwave radiation and 320 controls. Individuals whose military records showed them to be primarily engaged in the operation or maintenance of radar equipment and who had served in their occupations the longest were selected. For the control group, the primary criterion was that individuals chosen had not been engaged in any duties that permitted actual or potential exposure to radar. The data consisted of medical histories and results of an ophthalmic examination accomplished in a presumably double-blind fashion. Five board-certified (or eligible) ophthalmologists conducted 80% of the examinations. The occurrence of lens anomalies, including opacities, vacuoles, and posterior subcapsular iridescence, was similar in the two groups. One notable finding was a difference in the frequency of anomalies between control and exposed individuals who had a family history that included diabetes mellitus, nontraumatic cataract, glaucoma, or grossly defective vision. Lens changes were detected in 17% of the controls with such a family history, whereas, in the comparable exposed group, 29% of the individuals with this type of family history had lens changes.

Shacklett et al (*@MR0294*), in 1975, presented the results of eye examinations of various military personnel exposed to microwave radiation. The retrospective study included 817 subjects: 477 had been exposed to microwave radiation and 340 were not known to have been exposed. Eight different Air Force bases were visited between November 1971 and December 1974. Selection of exposed and unexposed personnel was the responsibility of local unit commanders. Subjects were separated into exposed and control groups according to age; most were in the 20-29 and 30-39 age ranges. The same examining ophthalmologists performed all the clinical diagnoses, and standardized diagnostic criteria were established. Analysis indicated an increased incidence of lens changes with increasing age for both groups. The examinations revealed no significant differences between exposed and nonexposed groups with respect to the presence of opacities, vacuoles, and posterior subcapsular iridescences. No attempt was made to correlate effects with differences in exposure due to geographic location or type of radar equipment.

Tengroth and Aurell (*@MR1928*) and Aurell and Tengroth (*@MR0005*) described an investigation of retinal changes in individuals exposed to microwaves. The study population consisted of 98 workers in an electronics plant in Sweden. Of this group, 68 individuals had been exposed to microwaves in the testing of radar equipment and components, whereas 30 had not been exposed and were used as controls. Two ophthalmologists performed all examinations. Each examinee's pupils were dilated and then illuminated with a slit lamp. The presence of lens opacities with a diameter of more than 0.5 mm or a high concentration of smaller opacities in the subcortical region were the major diagnostic indices. Retinal lesions were noted if detected in the central part of the fundus. Such lesions were characterized by their resemblance to chorio-retinal scars after inflammatory reactions. The number of lens opacities was significantly higher in exposed persons than in control individuals. This was true in younger age groups as well as in older groups, although mention was made of the difficulty of differentiating between senile cataracts and those caused or influenced by microwave exposure in older individuals. Retinal lesions were also more frequent in the exposed group. In the exposed group, testing personnel had greater numbers of lens opacities and retinal lesions than did laboratory personnel. A detailed statistical evaluation of the data was not made.

Hathaway et al (*@MR0020*), in 1977, reported the results of ocular examinations of military personnel who had worked with microwave equipment at three installations, all in the southwestern United States. The examination teams comprised two or three optometrists, with a different team used at each installation. Collected data consisted of medical and occupational histories or a brief questionnaire that included the type of microwave equipment currently in use, the length of time on the present job, past work with microwave devices, history of any past overexposures, and identification of any current or past visual disturbances. The total sample consisted of 705 workers, and the statistical analysis included multiple regression techniques. Diagnoses consisted of identifying the presence or absence of opacities, vacuoles, and posterior subcapsular iridescence.

Initial analysis showed that minute lens defects (particularly opacities and posterior subcapsular iridescence) were positively correlated with years of work with microwave equipment ($P<0.01$) (*@MR0020*). However, this was shown to be an artifact when the data were corrected for age. Overall findings supported the conclusion that no lenticular defects could be attributed to work with microwave radiation. The value of this study was limited by the lack of an appropriate unexposed control group, quantification of exposure, and standardized diagnostic criteria.

In a 1974 report, Zydecki (*@MR1799*) discussed the establishment of diagnostic criteria for evaluating lens translucency and the use of these criteria in examining a group of individuals differing in the extent of workplace exposure to microwave radiation. The study population consisted of 3,000 individuals separated into three groups. Group 1 contained two subgroups, one of 542 individuals exposed to microwaves at power densities between 0.1 and 1 mW/cm^2, with potential short-term exposure at 6 mW/cm^2, and the other of 458 individuals exposed to microwaves at 0.01 mW/cm^2 or less. Each individual in group 1 had been exposed for an average of 4 h/d for 1-15 years. Group 2 consisted of 1,000 individuals similar in age to those in group 1 and not exposed to microwaves in their workplace. Individuals in group 3 consisted of young people aged 5-17 years. Ocular examinations of dilated pupils were performed with a slit lamp. The degree of lens translucency was expressed on a 5-point scale based on the number and size of opacities detected.

The number of lenticular opacities was found to be significantly greater in the older individuals examined (*@MR1799*). Exposed individuals had significantly greater numbers of opacities than nonexposed subjects. Decreased lens translucency appeared to depend more on power density levels than on the duration of exposure. Individual data on exposure to microwave radiation were not available; sample selection criteria were not discussed and the representativeness of the samples is therefore questionable. Age distributions were not presented, and statistical testing for significant associations was mentioned but not presented.

Monayenkova and Sadchikova (*@MR1118*), in a 1966 report, discussed the effect of microwave exposure on the human circulatory system. Measurements were made of ECG, arterial blood pressure, minute volume of the heart, peripheral resistance, and vascular muscle tone. The sample of individuals examined consisted of 34 persons periodically exposed to "SHF" microwave radiation at up to several milliwatts per square centimeter. These individuals had been occupationally exposed for 5-15 years or more, and they ranged in age from 30 to 49 years. Although a control group was mentioned, selection of subjects for this group was not described. "Severe or moderately severe symptoms," such as pricking, stabbing, or constricting pains in the region of the heart and increased heart rate, were reported by 25 persons. Deviations in the functional state of the circulatory system, ie, variable blood pressure, abnormal minute volume, increased peripheral resistance, and increased elasticity of blood vessels, were found. Such changes in the ECG as sinus bradycardia and delays in conductivity were noted. This study was clinical in nature and not a rigorous epidemiologic investigation. In addition, quantitative data on many parameters were not reported, so that the significance of the results cannot be evaluated adequately.

Drogichina et al (*@MR0634*), in 1966, presented the results of clinical observations recorded over 10 years on 73 men and 27 women exposed to microwaves in the USSR. Although exposure levels were not quantified, all the subjects were occupationally involved with "SHF" electromagnetic fields during long periods of time at radiation levels reportedly up to several milliwatts per square centimeter. The study focused on autonomic and cardiovascular disorders, the most severe of which were characterized by angiospastic reactions, cerebral autonomic vascular attacks with increased arterial pressure, and coronary spasms with definite ECG changes. Symptoms of pain in the cardiac region were reported by 49 subjects. Indications of autonomic instability (variable pulse and blood pressure) were noted in 61 persons. Symptoms generally subsided after 1-2 weeks, but in some cases not for 2-3 years, following cessation of work around radiation sources. The value of this study must be questioned in view of a lack of control subjects, lack of quantified exposure data, inability to determine source and frequency of electromagnetic radiation, and lack of statistical analysis of the data.

In 1970, Glotova and Sadchikova (*@MR0084*) reported their observations on 90 men and 15 women who had been occupationally exposed to microwave radiation (specified only as in the 30-GHz range and at power densities of several milliwatts per square centimeter) for at least 5 years. Most of the irradiation had occurred during the initial work experience. Men under 40 years of age comprised 78% of the subjects. Two groups of similar age and exposure were studied. Group 1 contained 36 persons who had complained of weakness, headache, and insomnia. Hypotension and sinus bradycardia were also common findings, but physical and ECG examinations did not reveal any pathologic changes. Group 2 consisted of 69 patients with autonomic-vascular dysfunction. Indications of autonomic instability, such as headache, tremor, fainting, tachycardia, and hypertension, were common. The authors concluded that there was a positive correlation between cardiovascular changes and long-term exposure to microwave radiation. No control subjects were used for comparison, however, and the criteria of selection for the study sample were not discussed.

Sadchikova and Nikonova (*@MR0287*), in 1971, presented results of a clinical study designed to detect changes in the health status of individuals occupationally exposed to microwave radiation. Three separate groups were included. The first consisted of 83 men and 17 women periodically exposed at radiation intensities of up to "several" milliwatts per square centimeter. The second group consisted of 91 men and 24 women employed at the same plant, whose exposure did not exceed "several hundred parts" of a microwatt per square centimeter. A control group consisted of 100 men who had worked at the same plant but who had not been exposed to microwaves. The exposed workers had been involved with the repair or testing of complex radio equipment for radio position finding. Although all groups were considered to be comparable with regard to sex and age, distribution of these factors within groups was not noted. The age of most subjects was 40 or less, and 84% of group 1 and 78.2% of group 2 had been exposed for 5-10 years. The second group was accepted for employment after the introduction of protective shielding devices.

Specific findings on the nervous and cardiovascular systems of workers were presented (*@MR0287*). The investigators noted higher incidences and a more serious nature of complaints of weakness, of marked ECG changes, and of neurologic symptoms in the first group of subjects. The second group had a lower incidence of complaints of weakness ($P<0.001$), with autonomic vascular disorders similar to those found in the first group (29.6±4.2% vs 30±5%). Both exposed groups experienced a significant increase in bradycardia ($P<0.001$). A moderate leukopenia was established in the first group (47±6% of the cases vs 15±1.5% of the controls) but not in the second exposed group (12±4%).

More recently, Sadchikova (*@MR1757*), in 1974, reported the results of a medical survey of workers engaged in the regulation, tuning, and testing of radio equipment emitting microwave radiation. The workers were described as predominantly young men with 5-15 years of work experience. One group of 1,000 individuals was exposed at power densities ranging up to "a few mW/cm^2." A second group (180 subjects) was exposed at power densities not exceeding "several hundredths of a mW/cm^2." A matched, nonexposed group of 200 persons served as controls. The incidence of signs and symptoms, such as a feeling of heaviness in the head, fatigue, irritability, increased sweating, cardiac pain, and bradycardia, was significantly higher in the exposed men than in the controls. However, the data presented did not show a consistent pattern between power density and incidence of symptoms. Additional data relating incidence with duration of exposure indicated that most signs and symptoms were more prevalent after longer exposures. Other effects observed in the exposed workers were (1) slight decreases in RBC, WBC, and thrombocyte counts, (2) EEG changes, and (3) decreased response to glucocorticosteroids. The author noted that although symptoms tended to decrease after removal of a subject from the work environment, they increased again when the individual returned to work. However, data were not supplied to support this statement. Cessation of work reportedly resulted in stabilization or recovery from microwave-induced changes, but supporting data were not provided.

In a 1973 paper, Medvedev (*@MR1081*) examined cardiovascular diseases in relation to microwave exposure. The study population contained 80 men who were employed at the time of the study in engineering or administrative occupations but had been exposed to microwaves between 1948 and 1967. They had not had contact with such radiation for the past 4-7 years. Also included was a control group of 80 men. The sample was purposely selected so that older individuals could be studied. Exposed individuals and controls were stated to be "similar" in age, but the age distribution of individuals in each group was not presented. The exposure to microwave radiation experienced by the exposed group was estimated at 10 mW/cm^2 for 7 h/d throughout the course of employment. Thirteen individuals in the exposed group had abnormal ECG's, whereas only 4 of the controls had abnormal ECG's. Abnormal blood lipid indices and ischemic heart and hypertensive diseases were also more prevalent in the exposed group. Medvedev concluded that long-term exposure to microwaves facilitated the development of cardiovascular disorders, particularly in persons predisposed to such disorders. However, the significance of his data was limited by the use of nonspecific diagnostic indices, the failure to control for all potential confounding variables, a general lack of competent analytic and sampling statistics, and questionable quantification of exposure.

Kleyner et al (*@MR0873*), in 1975, presented the results of a comprehensive clinical study investigating the effects of workplace exposure to microwaves in the USSR. Fifty female welders of plastic items whose exposures to microwaves were between 45 and 160 V/m and a control group of 50 workers who were not exposed to microwaves were selected from the same factory and examined at the same time. In the exposed group, young workers predominated (41 under 40 years, 9 above 40 years) with relatively short working experiences (30 persons with 3-5 years). The age distributions within the two groups were said to be comparable but were not described in detail. Significant differences between the exposed and the control groups with respect to complaints were detected. Signs and symptoms commonly exhibited by exposed individuals (but seldom by control subjects) included headache, weakness, sleepiness, gastric hyposecretion in response to a food stimulus, decreased secretion of 17-ketosteroids, reduced urinary levels of catecholamines, and lens opacities. Also observed were disturbances in protein- and carbohydrate-forming functions of the liver and a disorder in the functional state of the pancreas. The authors noted that most of the changes seen were reversible and did not result in a loss of working capacity. A relationship between an increase of functional nervous system disorders and an increase in the length of workplace exposure was also noted, but relatively little data were provided to support this conclusion. In addition, no information was provided on other potentially harmful agents to which these workers may have been exposed.

In two 1969 papers, Fofanov (*@MR0079,@MR0691*) reported the results of examinations of 30 men (aged 25-40) who had worked with microwave-generating equipment six to seven times each month for 30-40 minutes. Eight had been engaged in this work for less than 5 years, 10 for 5-10 years, and 12 for more than 10 years. The equipment produced "UHF" irradiation at 10-500 $\mu W/cm^2$. The 30 men were admitted to a clinic for 14-20 days and during this period were extensively examined. No control subjects were studied; the values for hematologic parameters were compared with "normal" values from the literature. No corrections for age were made. The principal findings were a tendency in all the men toward bradycardia, slight decreases in cardiac output, evidence of altered function of the autonomic nervous system, and adaptive changes in the endocrine system. There was no appreciable change in mean blood pressure for the group. A number of nonspecific conditions, eg, weakness, apathy, and irritability, reportedly affected some men.

Barron et al (*@MR0856,@MR0857*), in 1955, described a study conducted to evaluate changes in various physical and functional attributes of radar personnel employed by a large airframe manufacturer. The hypothesis being examined was whether prolonged (years) or short-term (months) exposure to microwave radiation resulted in any form of biologic damage. The radar frequencies to which personnel had been exposed included S-band (2.88 GHz) and X-band (9.375 GHz). Exposure time and field power density were not given, but zones at various distances from the antenna defining three ranges of power densities were specified. In zone A the minimal power density was 13.1 mW/cm^2, zone B included the region from 13.1 to 3.9 mW/cm^2, and zone C was limited to lower power densities and was ignored. A total of 226 subjects with histories of radar contact was identified, and 88 individuals with no history of radar involvement were selected as controls (*@MR0856*). Personnel were grouped by years of exposure.

A significant decrease below the mean normal in the count of polymorphonuclear cells in the blood was reported in 25% of radar workers vs 12% of controls (*@MR0856*). An increase in the proportion of monocytes above 6% of all leukocytes and of eosinophils above 4% was also observed for some of the exposed group. Although eye examinations revealed a large number of ocular anomalies in the radar personnel, their principal causes were known and, except in one case, not related to exposure. Capillary fragility was found to be significantly higher in the controls than in the exposed workers. One hundred exposed subjects were reexamined 6-9 months later. A decrease of more than 10% in RBC counts was observed in 42% of the subjects, whereas increases in the WBC count and in the percentage of polymorphonucleocytes were observed in 58 and 35% of the subjects, respectively. There were no significant changes in blood platelet counts. The hematologic findings were viewed as paradoxical and difficult to interpret; normal variation and the lack of controls make these changes of uncertain significance. The small sample size, lack of description of standardized diagnostic criteria, relatively unsophisticated statistical techniques, questionable comparability of exposed subjects and controls (eg, different age distributions), and inability to quantify bias from examiner variability limit the usefulness of this study.

In a later report published in 1958, Barron and Baraff (*@MR0170*) retracted their earlier results showing changes in polymorphonuclear cells, monocytes, and eosinophils and attributed the changes noted earlier to a variation in interpretation. This later report served to update the previous work, and it involved periodic examinations of 335 adult aircraft workers exposed intermittently to 0.4- to 9-GHz radiation with peak power output exceeding 1 MW. No significant differences were noted between exposed individuals and controls with respect to RBC, WBC, or platelet counts.

The hematologic systems of 100 workers, aged 25-40, who had been exposed to "SHF" radiation for 1-8 years were examined by Gembitskiy et al (*@MR0739*) in 1969. Power densities were not specified except to note that they occasionally exceeded 10 $\mu W/cm^2$. The workers complained of general weakness, and hypotonic neurocirculatory dystonia was observed. A 10% increase in thyroid function (measured by uptake of ^{131}I) and a decrease in functional capability of the pituitary adrenal cortex system were found. Hemoglobin concentration and erythrocyte count were normal, but deviations in leukocyte count were noticeable. Both leukopenia and leukocytosis were evident to equal extents throughout the population. Bone marrow showed no obvious morphologic changes.

A 1974 study by Sokolov et al (*@MR2667*) investigated the influence of workplace exposure to microwaves on the blood. The study population consisted of 115 men and 16 women. Most were 40 years of age or less and had been employed for 5-10 years or longer. All had reportedly been exposed to microwave radiation at power densities of "several" milliwatts per square centimeter. Blood analyses showed decreases in the concentrations of thrombocytes and leukocytes. However, the hematologic changes noted were not extensive, did not appear in all cases, and did not give evidence of a tendency to progress. Hematopoiesis and blood indices returned to normal when exposure was ended.

Although control subjects were mentioned (800 clinically healthy people), detailed comparisons were not made.

Observations on 38 workers at two different facilities using RF and microwave radiation were reported by Stefanov et al (*@MR1405*) in 1973. Arterial blood pressure, pulse rate, skin temperature, blood cholinesterase activity, hemoglobin content, erythrocyte and leukocyte counts, attention span, and speed and accuracy of information processing were studied. The small number of exposed subjects was compared with an even smaller number (12) of control subjects. One group of 18 worked at a naval radio station with equipment generating 2- to 20-MHz radiation at power levels of 5-20 kW. A second group, consisting of 20 persons with an average age of 34 and an average of 6 years' experience, worked at a radio relay station. These individuals had been exposed to PW 2.9-GHz radiation (power output of 40 W), to 3.6- to 4.0-GHz radiation (7-W power output), and to 194- to 200-MHz radiation (150- to 600-W power output). No values significantly outside the physiologic norms were recorded, except for monocytosis in the first group and a tendency towards leukopenia in the second group.

In 1966, Baranski and Czerski (*@MR0850*) reported the results of hematologic studies in workers (number not given) exposed to microwaves. The subjects were separated into three groups based on degree of exposure. However, details of the method of determining the extent of exposure were not given. One group included individuals with the "lowest" exposure, and another group consisted of workers with a "somewhat higher" exposure. The third group was engaged in the repair and production of microwave generators. Workers were further separated into the following four groups according to their work experience: those employed less than 1 year, 1-3 years, 3-5 years, or 5-10 years. Hemoglobin concentration and RBC and WBC counts were determined in all workers. Reticulocyte and platelet counts were measured in selected cases (selection criteria not explained). Bone marrow studies were done in 19 subjects. Insignificant differences from normal were found in RBC counts. Similarly, WBC counts were within normal limits, regardless of exposure. Of the persons examined, 40-50% in all job categories had moderate decreases in their platelet counts. In workers with low to medium exposure for over 5 years, a tendency toward lymphocytosis (relative and absolute) associated with eosinophilia was found. For persons with a high degree of exposure for over 5 years, lymphocytosis (relative and absolute) became associated with both eosinophilia and monocytosis. Less frequently, workers had neutrophilic leukocytosis. In the 19 persons examined, bone marrow was found to be essentially normal. The lack of detailed information in this paper on exposure and number of subjects makes the conclusions of the authors questionable.

A survey of 123 clinically healthy radio engineers and technicians was reported by Volkova and Fukalova (*@MR2673*) in 1974. Control data were not given. The blood phagocytic and bactericidal activities, the microbial "autoflora" count within the mouth, and the bactericidal activity of the skin were compared with published values. At three stations where the radiation field strength did not exceed 20 V/m, the values of the four indices were within the normal range. However, at a fourth station where field strengths were higher than 20 V/m, the workers had a mean 50% inhibition of phagocytic activity and a fourfold increase in the concentration of microbial "autoflora."

In 1978, following 3 years of observation of 72 engineers and technicians of microwave generators, Zalyubovskaya and Kiselev (*@MR3066*) reported that long-term irradiation with 30- to 300-GHz microwaves at power densities as high as 1 mW/cm^2 produced alterations in immunocompetence. Thirty nonexposed workers served as the control group. The evidence consisted of a small but significant ($P<0.01$) increase in the concentration of autoflora microbes in the oral cavity, decreases in the bactericidal activity of the skin, decreases in lysozyme and complement titers, and decreases in the phagocytic activity of neutrophils. The concentrations of leukocytes and segmented neutrophils in the blood also reportedly decreased, whereas the concentration of lymphocytes increased. Fatigue, sleepiness, headaches, and reduced memory capacity were common subjective complaints of the workers, who ranged from 20 to 50 years in age and had worked with the generators as long as 10 years. The only other observed effects were decreases in hemoglobin and erythrocyte concentrations and the color index of the blood, plus hypercoagulability. Pulse rate, blood pressure, and body temperature were normal.

D'yachenko (*@MR1835*), in 1970, reported investigating the pathogenesis of functional disturbances of the thyroid in selected individuals chronically exposed to microwaves. Thyroid function was measured by absorption of ^{131}I. The study population consisted of 38 men who had been occupationally exposed to microwave radiation in the 1-cm (30-GHz) range for 3.5 hours during each working day for 3-15 years. Control data were not provided. The daily absorption of ^{131}I by the thyroid was normal in 31 individuals but somewhat high in 7. The author interpreted the latter finding as indicating that microwave radiation had affected the CNS and that the altered function of the thyroid was a general adaptational change. No direct evidence for an effect on the function of the CNS was provided, however.

In 1973, Klimkova-Deutschova (*@MR1866*) described a study of 162 workers who had been exposed to radiation in the frequency range of 3-30 GHz (mainly PW). Seven other groups of workers in several industrial situations, such as metal and plastics welding and radio and TV transmission, were included for comparison. Headache, fatigue, and excitability developed in a statistically significant number of workers. Indications of disturbances of the autonomic nervous system and cerebellum were also reported. Electroencephalographic recordings contained evidence of synchronization of cortical discharges and slowed rhythms. The temperature of the CSF was elevated to the greatest extent in the cisterna magna. These symptoms and signs were not significantly correlated with age and were considered by the author to be characteristic of microwave exposure.

A 1975 report by Baranski and Edelwejn (*@MR0006*) examined three groups of workers exposed to microwave radiation. Groups were classified by levels of exposure; medical histories, physical examinations, and EEG's were recorded for each subject. The groups were then further separated according to duration of microwave exposure. An undetermined number of workers complained of headaches and profuse sweating, which were proportional to the duration of radiation exposure. Workers with the greatest exposure were found to have "flat" EEG's. The investigators could not draw any conclusions because of a lack of appropriate controls and problems involved in quantifying exposure. However, in an earlier report published in 1962, Edelwejn and Haduch (*@MR1836*) had concluded that individuals in their study exposed to microwaves for more than 3 years had EEG's with diminished "alpha-wave coefficients."

Sigler et al (*@MR1373*), in 1965, and Cohen and Lilienfeld (*@MR0537*), in 1970, presented results of a two-stage epidemiologic study designed primarily to evaluate the relationship between mongolism (Down's syndrome) and parental exposure to ionizing radiation. However, ancillary results related to microwave exposure were also presented. The study included 216 cases of parents with mongoloid children and the same number of control parents. A single-blind technique was used in the interviews with the parents, ie, interviewers were not informed which parents were controls. Microwave exposure information was available only for fathers, and exposure of mothers to microwave radiation was not investigated. The interviews revealed that 63.1% of the fathers of mongoloid children had served in the armed forces vs 56.6% of the control fathers.

However, this difference was not statistically significant. The authors noted that 8.7% of fathers of mongoloid children had had contact with radar vs 3.3% of control fathers (P approximately 0.02); however, the amounts of exposure were not quantified. Radar contact had occurred when the father was either a radar technician or a radar operator. Information on maternal contact with radar was not presented.

Although the study found indications of an association between maternal exposure to ionizing radiation and mongolism, no such correlation was found for the fathers (*@MR1373,@MR0537*). The possible relationship between mongolism and paternal radar exposure, however, led the authors to conclude that this potential association warranted further investigation. In particular, the investigators pointed out that a small amount of ionizing radiation, in addition to microwave radiation, may be emitted by high-voltage radar equipment.

A replicative study published by Cohen et al (*@MR3024*), in 1977, failed to confirm the higher incidence of paternal radar-microwave exposure in fathers of Down's cases suggested in the earlier study. However, the authors noted that such a relationship could not be completely ruled out pending further investigation.

In a 1975 study of gonadal function in workers exposed to microwave radiation, Lancranjan et al (*@MR0235*) presented findings related to long-term exposure. The study population consisted of 31 male technicians exposed to microwave radiation and 30 male unexposed controls. No explanation was given by the authors of the criteria used in selecting the sample. The mean age of the subjects was 33 years; 28 were less than 40 years old. Workplace exposure to radiation with frequencies between 3.6 and 10 GHz varied from 1 to 17 years (mean 8 years). The intensity of exposure was in the range of "tens to hundreds" of microwatts per square centimeter. Indices were developed to measure changes in gonadal function, and the findings revealed statistically significant alterations in spermatogenesis in exposed workers. Specific differences included the number of spermatozoa per milliliter of ejaculate ($P \leq 0.02$), percentage of motile spermatozoa per ejaculate ($P<0.001$), and percentage of normal spermatozoa per ejaculate ($P<0.001$). Followup examinations performed 3 months after the cessation of exposure found an improvement in spermatogenesis in two-thirds of those exposed.

A recently published (1978) study by Lilienfeld et al (*@MR3075*) analyzed the medical records of 1,827 US Department of State employees and their dependents assigned to the US Embassy in Moscow between 1953 and 1976. The health status and mortality of these individuals were compared with those of 2,561 State Department employees and their dependents from other Eastern European embassies. During the 1953-76 period, microwave radiation was reportedly beamed at the US Embassy in Moscow, thereby potentially exposing embassy employees. During this period, maximum exposure of the chancery building ranged from fractions of a microwatt per square centimeter to 15 $\mu W/cm^2$, 18 h/d. The biostatistical study found no evidence that the Moscow group had experienced any higher mortality from any specific cause of death, including malignancy. In addition, no relationship was found between the incidence of nonfatal health effects and exposure to microwaves. The authors cautioned, however, that the population studied was relatively young, and they suggested that long-term followup studies should be made.

Correlation of Exposure and Effect

(a) Absorption of Radiofrequency/Microwave Energy

The extent of an effect produced by exposure to RF and microwave radiation often has been assumed to depend on the rate and amount of energy absorbed and on the distribution of absorbed energy. The absorption of electromagnetic energy depends on the frequency of the radiation and on the size, shape, orientation, and dielectric properties of the object(s) being irradiated (*@MR0423,@MR0604,@MR0731,@MR0732,@MR2925*). For example, maximum SAR during whole-body irradiation of small animals reportedly occurs at frequencies between approximately 0.5 and 3 GHz (*@MR0473,@MR2925*).

For humans, a maximum whole-body SAR occurs around 60-100 MHz with a peak at about 70 MHz (*@MR2089,@MR2925*). At frequencies below 30 MHz, absorption decreases markedly (*@MR2768*) and is also much less at frequencies above about 500 MHz (*@MR2089,@MR2925*). In addition, at frequencies near 70 MHz, local absorption in the legs and neck is considerably higher than is human whole-body average absorption (*@MR1896,@MR3090*). Recent data indicate a resonant frequency for the human arm at about 150 MHz (*@MR1896*) and for the human head at about 350 MHz (*@MR3027*).

Modeling data using prolate spheroids have shown that absorption also varies according to the polarization of the incident wave, with the greatest absorption occurring when the E-vector and the long axis of the spheroid are coplanar (*@MR2089,@MR2925*). Ground resistance is another variable that can alter resonant frequencies (*@MR2925*). Peak absorption in the presence of ground effects occurs at frequencies about one-half those for bodies isolated in free space (*@MR2089*). However, a worker who is not grounded, eg, a person wearing nonconducting shoes, would be unaffected by this, since a small separation that breaks electric contact with the ground plane eliminates most of the ground effect (*@MR1896*). Figure III-1 illustrates the frequency dependence of whole-body energy in humans and rats exposed in the far field.

It should be emphasized that, due to the differences in absorption characteristics discussed above, a dose reported to produce a given biologic effect in animals may be different from the dose required to produce a similar effect in humans at the same frequency if, indeed, such an effect occurs in humans at all. In addition, it is not clear that an effect produced in animals at one frequency would be produced in humans at another frequency.

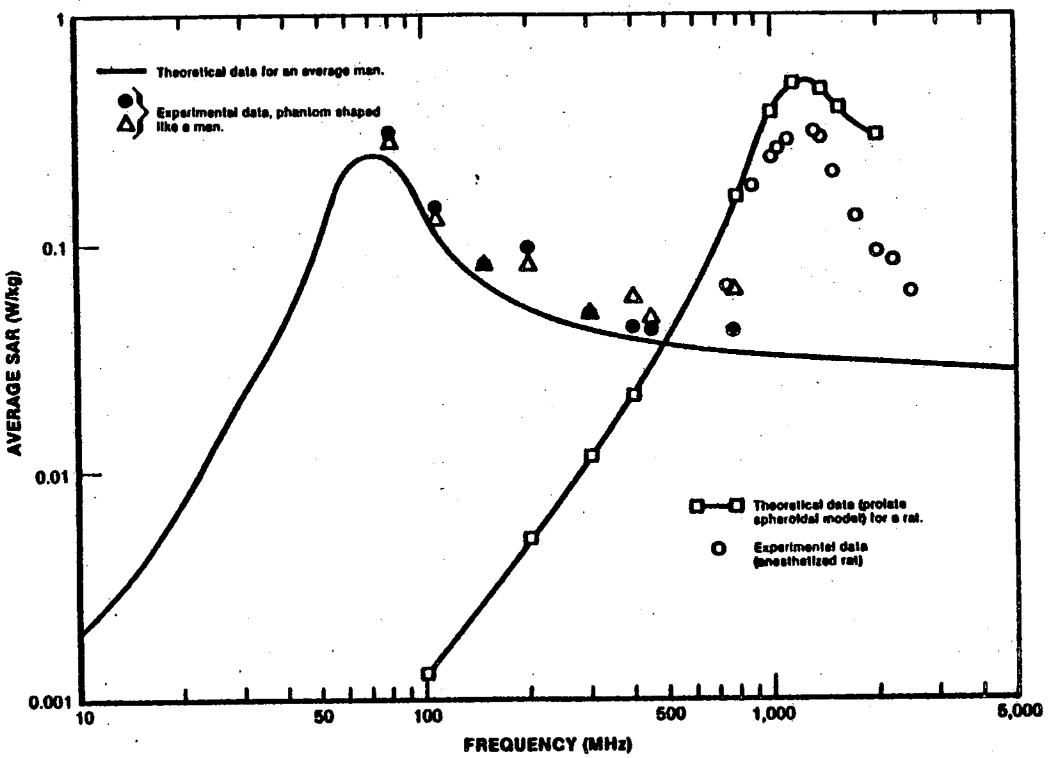

FIGURE III-1. CALCULATED AND MEASURED VALUES OF THE AVERAGE SPECIFIC ABSORPTION RATE (SAR) FOR MODELS OF AN AVERAGE MAN (E-POLARIZATION) AND FOR A 96-g RAT (K-POLARIZATION). Based on an incident power DENSITY OF 1 mW/cm^2 (far field)

Adapted from reference @MR2925

The early work of Schwan and Li (*@MR1337,@MR1338*) involved measurements and calculations that showed that an incident power density of about 10 mW/cm^2 of microwave radiation can be tolerated by the human body without producing a net rise in body temperature. However, the dependence of absorption on frequency must also be considered. If the human whole-body SAR is divided by the BMR for humans, a ratio is obtained that provides a measure of the thermal load incurred due to a known incident power density (*@MR3086*). Table III-15 illustrates how this ratio varies with frequency at two incident power densities. In the region of human whole-body resonance (60-80 MHz), this ratio reaches a maximum value (about 0.16 for an incident far-field power density of 1 mW/cm^2 or about 0.8 for an incident far-field power density of 5 mW/cm^2). The ratio drops off rapidly on either side of this peak, and below 10 MHz the ratio can be calculated to be less than 0.001 for an incident power density of 1 mW/cm^2 (see (*@MR2925,@MR2768*)).

In fatty tissues and in tissues with a high water content, such as muscle, the depth of penetration of microwave energy decreases rapidly with increasing frequency above 500 MHz (*@MR1326,@MR0937*). At frequencies between 10 and 300 GHz, the skin absorbs essentially all of the electromagnetic energy incident on it, and primarily the surface of the human body is heated (*@MR1326*). Human skin has been found to absorb most of the energy at frequencies of 3 GHz and above (*@MR0547,@MR0548,@MR0990,@MR1940*), and at these frequencies the subjective perception of warmth is greatest due to the large number of nerve endings in the skin.

TABLE III-15

RATIO OF SPECIFIC ABSORPTION RATE TO BASAL METABOLIC RATE

FOR AN AVERAGE MAN EXPOSED AT FAR-FIELD INCIDENT POWER DENSITIES

OF 1 mW/cm^2 AND 5 mW/cm^2

Frequency (MHz)	SAR/BMR	
	1 mW/cm^2	5 mW/cm^2
10	0.001	0.007
20	0.006	0.03
50	0.06	0.29
60	0.16	0.80
80	0.16	0.80
100	0.12	0.60
200	0.05	0.26
500	0.04	0.19
1000	0.03	0.15
2000	0.03	0.13
5000	0.03	0.13
10,000	0.03	0.13
20,000	0.03	0.13

Adapted from reference @MR3086

(b) Acute Effects

The production of heat in humans by RF and microwave radiation was one of the earliest biologic effects observed and studied (*@MR0921,@MR0744, @MR0548,@MR0497,@MR0440*). The sensation of warmth may serve as an indication of intense acute exposure in the microwave (GHz) region, as was documented in the case of a worker who received a high dose of microwave radiation

(*@MR1155*). However, experiments on human subjects have indicated that the subjective awareness of warmth is not a reliable indication of the intensity of microwave exposure (*@MR0547,@MR1327*).

Animal experiments have shown that acute lethality is directly related to the heating effect of exposure to RF and microwave radiation. Exposure of mice (*@MR1415,@MR2631,@MR1402*) to 9- to 10-GHz radiation and of rats (*@MR0134*) to 0.95- to 7.44-GHz radiation indicated that, over the range of power densities investigated, the exposure time necessary for the production of lethality is inversely related to the power density.

In mice, Jacobson and Susskind (*@MR2631*) showed that 50% mortality could be produced at 10 GHz after 11.5 minutes of irradiation with an incident power density of 120 mW/cm^2 or after 2.3 minutes with 440 mW/cm^2. Lethality was correlated with a 6-7 C rise in rectal temperature, and the minimum power density necessary to produce a definite increase in rectal temperature (0.1 C) was estimated from theoretical considerations to be 10 mW/cm^2. However, a 23-minute exposure of mice to a frequency of 9.3 GHz (PW) at average incident power densities of 58 mW/cm^2 and below produced no mortality in mice, as reported by Prausnitz and Susskind (*@MR1251*).

In experiments with dogs, mortality was also correlated with a rise in rectal temperature of about 6 C (*@MR0932*). Mean exposure time to produce death was about 268 minutes at 2.45 GHz and 800 mW/cm^2. At 200 MHz, however, a lower range of power densities (165-330 mW/cm^2) and of periods of exposure (15-23 minutes) produced lethality in dogs (*@MR2206*). Modeling data have indicated that a resonant frequency for whole-body absorption by dogs exists in the frequency range of 100-300 MHz (*@MR2925*).

Short pulses of very high intensity microwave energy have been shown to be lethal to animals, and such radiation has been used in brain inactivation studies in mice and rats (*@MR1744*). In general, these experiments have involved 0.2- to 14-second exposures to output powers of 0.6-6 kW (see <u>Effects of Short Pulses of Radiation</u> for details and references). Brain temperatures of 70-90 C were produced, and mortality was directly attributable to the heating effect of microwave energy.

Most of the brain inactivation studies used microwave radiation at 2.45 GHz (in two studies, 2.75 GHz was used), a frequency near which resonance will occur in the rat. Studies at other frequencies are not known to have been performed. Extrapolating the results to humans is difficult. It is known, however, that 2.45-GHz radiation does not penetrate the human skull as effectively as radiation near the resonant frequency for the human head that reportedly occurs at about 350 MHz (see <u>Biophysical Principles</u>). Nevertheless, it can be assumed that the protein denaturation and fixation of tissue observed in the brain inactivation studies will occur in whatever region of the body such high intensity radiation penetrates. That is, it may occur over the entire frequency range in which the human body absorbs RF and microwave energy, 300 kHz -300 GHz, although the greatest hazard should exist in the range of resonant frequencies.

Also, relevant to consideration of biologic effects of short pulses of electromagnetic energy is a report by Kinosita and Tsong (*@MR3138*) describing hemolysis of RBC's in solution after a 20-μs exposure to a 370 kV/m E-field. Square-wave E-field pulses were found to increase the permeability of red cell membranes to sodium ions, presumably by creating pores that could be resealed by increasing the osmotic pressure in the suspending solution.

Experiments involving the exposure of animals to EMP radiation have failed to detect biologic changes after exposure (*@MR1381,@MR3143,@MR3139*). Although peak E-field strengths used in these experiments were extremely high (ca 450 V/m), it should be kept in mind that the pulse rise and fall was nearly instantaneous (>1 μs) and the pulse rate was generally 5 pps. Therefore, there should have been a minimal amount of energy transferred into the animals.

(c) Ocular Effects

Several reports have described the production of lens changes in humans that could have resulted from exposure to microwave energy. Hirsch and Parker (*@MR0820*) documented the loss of visual acuity in a microwave technician after long-term daily exposure at an estimated average power density of 5 mW/cm^2 and after 3 days of increased exposure at an estimated level of

120 mW/cm^2 for 2 h/d. Zaret (*@MR1514*) described three cases of cataract formation in workers allegedly exposed at high levels of microwave radiation during certain periods of the workshift. Other reports by Zaret described the development of cataracts in a woman allegedly exposed to microwaves leaking from an oven (*@MR0058*), the loss of vision in a worker after 27 years of working with microwave transmitters (*@MR1516*), and cataract formation in workers who reportedly were chronically exposed at "nonthermal" levels of "hertzian" radiation (*@MR1797*). The evidence for microwave involvement in at least some of these cases, and in another case described by Kurz and Einaugler (*@MR0234*), must be considered as circumstantial, however. In addition, a clinical study by Clark (*@MR0531*) reported no lens damage in approximately 75 patients who were treated with microwave diathermy for various ophthalmic diseases.

Numerous epidemiologic studies, most of which involved examinations for lens changes, have been made of populations exposed to RF and microwave radiation; the findings of these studies have often been contradictory, however. Some surveys of military personnel and civilians exposed to radar and other microwave radiation showed apparent positive correlations between microwave exposure and lens changes (*@MR0653,@MR0180,@MR0248,@MR1928,@MR0005, @MR1799*). Other studies, however, revealed no significant correlations in exposed workers or military personnel (*@MR0166,@MR0182,@MR0046,@MR0294, @MR0020*). Several studies noted that such factors as age (*@MR0154,@MR0294, @MR0020,@MR1799*) and medical history (*@MR0270*) must be taken into account when the data are analyzed. Apparently, these variables have often been neglected. Furthermore, it is difficult to determine which of these conclusions is correct, since many of these surveys reveal a lack of quantitation of exposure, fail to adequately report relevant variables, and show poor statistical analysis of data.

In studies of ocular effects in animals, rabbits have been used almost exclusively. This is because the rabbit eye is about 0.75 the diameter of, and is structurally similar to, the human eye. Little doubt exists that cataracts can be produced in rabbits and other animals by microwave radiation; however, it should be emphasized that in many of these studies radiation was concentrated on the eye, a situation that may not be relevant to most occupational situations. Furthermore, the exposures used in these experiments were relatively high (over 100 mW/cm^2).

Early reports described the development of microwave-induced cataracts in dogs (*@MR0571*) and rabbits (*@MR1265*). Certain thresholds of exposure seem to exist for the formation of cataracts. Carpenter et al (*@MR0782*) and Carpenter and Van Ummersen (*@MR0396*) conducted extensive studies in rabbits to measure cataractogenic thresholds. The exposure time required for cataract formation was found to be inversely related to the power density level. The lowest exposure level found to result in the production of lens opacities was 15 daily 60-minute exposures at 80 mW/cm^2 (CW 2.45 GHz). Single 60-minute exposures at either 40 mW/cm^2 or 80 mW/cm^2 did not produce lens opacities.

Other studies have determined minimum cataractogenic doses. Guy et al (*@MR1649,@MR0088*) found that the minimum dose necessary to produce cataracts in rabbits, at a frequency of 2.45 GHz, was an incident power density of 150 mW/cm^2 given for 100 minutes. These animals were irradiated in the near field, however, making power density measurements somewhat tenuous. Williams et al (*@MR1488*) also measured cataractogenic thresholds in rabbits at this frequency but found them to occur at much higher power densities (290-590 mW/cm^2).

Other experiments at relatively high power densities have revealed ocular changes in rabbits including hyperemia, conjunctival congestion, and lens opacities. A dose-response relation was suggested in results by Appleton et al (*@MR0003*) using 3-GHz radiation at 100-500 mW/cm^2. Single and multiple 10-60 minute exposures at 2.8 GHz and 160-240 mW/cm^2 (*@MR0292*), and at 2,45 GHz and 165-250 mW/cm^2 (*@MR0056*), also resulted in the production of ocular changes.

Results of studies conducted at lower power densities for longer exposure periods have been less than conclusive. Balutina and Korobkova (*@MR0845*) observed the production of ocular changes at the microscopic level in rabbits exposed to 30-GHz radiation at 5-10 mW/cm^2, 1 h/d for 30 days. These lens alterations included capsular pigmentation, limited fiber edema, and vacuole formation. The reported effects were not evaluated in terms of cataract production, since no clinical changes were monitored. Tajchert and Chmurko

(*@MR1424*) described the production of microscopic lens changes in rabbits exposed to 3-GHz radiation at an average power density of 5 mW/cm^2. However, a recent study cited by BRH (*@MR1999*) reported a lack of cataract formation in rabbits exposed for 1 h/d for 12 weeks to a frequency of 2.45 GHz and an incident power density of 10-12 mW/cm^2 from a leaky microwave oven.

In summary, there are indications from a few case reports that high incident levels of microwave radiation may have contributed to the production of cataracts in the eyes of exposed humans. In addition, experiments using animals have confirmed that microwave energy at relatively high levels can result in the formation of cataracts, particularly when the energy is concentrated on the eye. There is also some evidence for ocular changes after exposure to lower levels of microwave energy. However, these observations are less conclusive than those resulting from exposure at high levels, and their relation, if any, to cataract production is unclear.

(d) Effects on the Neuroendocrine System

Alterations in certain neuroendocrine functions have been reported after exposure of animals to RF and microwave radiation. Alterations in levels of various hormones were observed after exposure of rats to 2.38 GHz at 0.01-10 mW/cm^2 (*@MR0307*), to 37-60 GHz at 1 mW/cm^2 (*@MR0749*), and to 2.45 GHz at 10-15 mW/cm^2 (*@MR0038*), 20 mW/cm^2 (*@MR1989*), 13-60 mW/cm^2 (*@MR0113, @MR1718*), and 36 mW/cm^2 (*@MR0836*). Ultrastructural changes in the pineal gland and increased secretion have been reported after multiple exposures of rats to 2.9 GHz at 15 mW/cm^2 (*@MR0524*). Increased iodine uptake and thyroid secretion have been reported after long-term exposure of rabbits to 3 GHz at 5 mW/cm^2 (*@MR0852*). Altered neurohormone levels were observed after exposure of rats to 3.0 GHz at 10 mW/cm^2 (*@MR0296*). Changes in hormonal levels at higher power densities have also been reported (*@MR0115,@MR1710*). In other animal studies, alterations were not observed in hormonal levels after microwave exposure to 2.45 GHz at 1-100 mW/cm^2 (*@MR0264,@MR2000*) and 2.87 GHz at 5-10 mW/cm^2 (*@MR1890*).

Increased urinary excretion of certain hormones has been noted in experiments involving multiple exposures of guinea pigs to 2.4 GHz at 7-18 mW/cm^2 (*@MR2383*). Serdiuk (*@MR2518*) reported increased urinary excretion of 17-ketosteroids after long-term exposure of rats and rabbits to 50 MHz at 0.5-6 V/m.

Increased urinary excretion of hormones was also reported by Dumanskii and Shandala (*@MR1832*) in experiments with rats and rabbits involving long-term multiple exposures to 50 MHz and 2.5 GHz at 1.9-10 $\mu W/cm^2$. However, no mention was made in this paper of the difficulty in accurately measuring power densities at these extremely low levels.

Recent experiments by D'Andrea et al (written communication, January 1979) failed to detect changes in adrenal weight or in urinary concentrations of

17-ketosteroids after multiple 2.45-GHz exposures (8 h/d, 5 d/wk for 16 weeks) of rats at 5 mW/cm^2. Similar experiments by Lovely et al (*@MR2006,@MR3087*) failed to detect alterations in urinary ketosteroids in rats exposed to 2.45-GHz radiation at 2.5 and 0.5 mW/cm^2, respectively, for 3 months.

Epidemiologic studies have been contradictory with regard to effects of RF and microwave radiation on the neuroendocrine system. Changes in certain hormone levels and neuroendocrine functions were reported in two studies of workers exposed to "SHF" radiation (*@MR2629,@MR0739*). Two other studies, however, found no significant differences between exposed and unexposed workers, and workers exposed to "SHF" and "radar" frequencies, with respect to levels of certain steroids and corticoids (*@MR0417,@MR0383*). In a study of workers exposed to 30-GHz microwaves, D'yachenko (*@MR1835*) found that levels of iodine uptake by the thyroid gland in 7 of 38 workers studied were somewhat higher than normal values.

Changes in the weights of the adrenal, pituitary, and thyroid glands have been reported in animal studies (*@MR2000,@MR2654,@MR2664*). One of these studies, described by Demokidova (*@MR2654*), involved exposure of rats for 1-4 months to 69.7 MHz at field strengths of 5-48 V/m (decreased thyroid and adrenal weights) and to 14.88 MHz at 70 V/m (decreased thyroid and increased adrenal and pituitary weights). The frequencies used in this study fell into the area of maximum human absorption of RF and microwave radiation (*@MR2925*). Another report by Demokidova (*@MR2664*) described changes in adrenal and pituitary gland weights of rats after exposure to 3 GHz at 153 $\mu Wh/cm^2$, and Guillet and Michaelson (*@MR2000*) found increased adrenal gland mass after exposure of rats to 2.45 GHz at 40 mW/cm^2. Lu et al (*@MR1989*), however, found no such changes in rats after 1- to 8-hour exposures to 2.45 GHz at 1-20 mW/cm^2.

(e) Effects on the Central Nervous System

Radiofrequency and microwave radiation reportedly induced tissue and biochemical changes in the CNS of animals at power density levels ranging from 0.03 to 80 mW/cm^2. The frequencies involved have been mostly limited to 1-3 and 10 GHz, which are in the range of calculated (and experimentally determined) resonant frequencies for maximum absorption in rats and mice (*@MR2925*). Microscopic tissue changes were observed after multiple irradiations of rats at 2.3 mW/g (*@MR1776*), of mice and rats at 10 mW/cm^2 (*@MR0420*), of rabbits at 5 mW/cm^2 (*@MR0006*) and 5-30 mW/cm^2 (*@MR0851*), and of cats at 5-30 mW/cm^2 (*@MR1902*). Similar changes were observed after single irradiation of hamsters at 10 and 25 mW/cm^2 (*@MR2937*). Neurotransmitter levels were altered after irradiation at 10 mW/cm^2 for 7 or 8 days (*@MR1391,@MR0335*) and at 20-80 mW/cm^2 for 10-60 minutes (*@MR3016*). Effects on the peripheral nervous system were noted at 1-10 mW/cm^2 (*@MR0799*) and after multiple exposures of rats to 37-60 GHz at reported levels of 1 mW/cm^2 (*@MR0749*). Negative results were described with regard to tissue changes after short-term irradiation at power densities up to 50 and 64 mW/cm^2

(*@MR0164,@MR1110*) and with regard to neurotransmitter levels after short-term irradiation at 40 and 80 mW/cm^2 and after multiple exposures at 10 mW/cm^2 (*@MR1010*). Some studies of RF and microwave effects on the CNS have involved an increase in the permeability of the blood-brain barrier after microwave exposure. This effect has been observed in rats after short-term irradiation at 1.2 GHz and 0.2-2.4 mW/cm^2 (*@MR3009*) and at 1.3 GHz and 0.03-3 mW/cm^2 (*@MR1736*) and in rats and hamsters after 2- to 8-hour irradiation at 2.4-2.8 GHz and 10 mW/cm^2 (*@MR2936,@MR2948*).

Bawin and coworkers (*@MR2856,@MR2871*) found increased efflux of Ca^{2+} from cerebral tissue following in vitro exposure to 147- and 450-MHz radiofrequency and microwave energy at power densities of 0.1-1 mW/cm^2. Blackman et al (*@MR3132*) obtained similar results. In addition, enhanced efflux of Ca^{2+} from the cerebral cortex has been reported after exposure of awake trephined cats to 450-MHz energy below 1 mW/cm^2 (*@MR2861*). These results have led to suggestions that RF/microwave-stimulated Ca^{2+} efflux may be related to reported effects on behavior and on the CNS (*@MR2856*).

Alterations in the EEG of animals have been produced during microwave irradiation at power densities as low as 0.02-1 mW/cm^2 (*@MR1551,@MR1839, @MR0768,@MR2634,@MR2668*) and up to 5 mW/cm^2 (*@MR0089,@MR0291,@MR0781, @MR0851*). One report (*@MR1832*) described EEG alterations in rats and rabbits after multiple exposures at power density levels (1.9-10 $\mu W/cm^2$) that are difficult to measure accurately with currently available instrumentation.

In another study (*@MR2518*), EEG changes were reported in rats and rabbits after long-term exposure to 50-MHz radiation at 0.5-6 V/m. The duration of irradiation in the above experiments ranged from 5 minutes to several days and up to 6 months. Epidemiologic studies have included data on EEG changes in humans (*@MR0006,@MR1866*) at reported power densities below 0.3 and up to 42 mW/cm^2. The effects were noted at frequencies presumably in the GHz range ("radar").

The auditory detection of pulsed microwave radiation has been well documented in humans (*@MR0711,@MR1648*). The effect was demonstrated to depend on pulse duration and repetition frequency (*@MR0703*). Furthermore, the threshold for the effect (40 $\mu J/cm^2$) was found to occur at relatively low energy densities (*@MR1648*). Several mechanisms, such as thermoelastic phenomena within the brain, have been proposed as the basis for the response (*@MR1696*), and the size of the skull seems to be an important factor in the phenomenon (*@MR0336,@MR1648*). Discussion of these mechanisms is germane to the realization of a possible direct effect of RF and microwave radiation on brain structure and function. Although many of the human studies on the auditory effect have been concerned with a subjective description of the response, animal experiments have attempted to determine the locus of action of RF radiation (*@MR0397,@MR2004,@MR2771,@MR1696*). Recent work by Cain and Rissman (*@MR3042*) has indicated a hearing threshold for 3-GHz microwave pulses (5-15 μs pulse width) of 2.3-20 $\mu J/cm^2$ for humans and small animals. Whether the "microwave hearing" effect constitutes an occupational hazard is not clear. No clearly adverse effects due to this phenomenon have as yet been demonstrated in humans or animals, and much further research is needed in this area.

(f) Behavioral Effects

Reports of RF and microwave-induced effects in humans have included such symptoms as weakness, irritability, headaches, hypertension, and insomnia (*@MR0006,@MR0084,@MR0287,@MR0739,@MR1866,@MR1757*). These observations, made during epidemiologic studies of groups of workers exposed for 1-17 years, have been associated with exposures to RF/microwave radiation at power densities reported to be as low as 0.01 mW/cm^2 (*@MR0739*) or lower (*@MR1757*). As with many other epidemiologic studies discussed in this chapter, however, deficiencies exist in several of these reports (see <u>Epidemiologic Studies</u>).

Numerous scientific analyses of the effect of RF and microwave radiation on animal behavior have been reported. Changes in motor ability (*@MR0221, @MR2325,@MR0644,@MR0843,@MR0976,@MR1869,@MR1991,@MR2141,@MR2274*), discrimination (*@MR0221,@MR1991*), learning (*@MR1146,@MR2268*), and operant conditioning (*@MR0051,@MR0076,@MR0094,@MR0225,@MR0804,@MR0871,@MR1608,@MR1676, @MR1697,@MR1822, @MR1992, @MR1759, @MR0707, @MR2944, @MR2421, @MR0749, @MR2518, @MR2077,@MR2274*) reportedly occurred in mice, rats, and monkeys. The frequencies involved ranged from 50-990 MHz to 2.45-60 GHz. Although most studies used power densities in the range of 5-50 mW/cm^2 (*@MR0051,@MR0094,@MR0225,

@MR0976, @MR1146, @MR1608, @MR1697, @MR1759, @MR0804, @MR2077, @MR1214*), effects were observed at levels as low as 0.01-0.7 mW/cm^2 (*@MR0707,@MR2944, @MR2518,@MR2141*) and in the range of 1-15 mW/cm^2 (*@MR2268,@MR2274,@MR1676, @MR2325,@MR0749*). Many of the studies were long-term experiments in which performance was measured during daily periods of irradiation. In some cases, effects were noted as early as the 1st week after the beginning of irradiation (*@MR1991, @MR2268*).

Frey (*@MR2944*) and Frey and Feld (*@MR0707*) reported behavioral changes in rats after exposure to PW 1.2-1.3 GHz at average power densities of 0.1-0.65 mW/cm^2. Mice exposed to 2.38 GHz radiation at 1 and 10 mW/cm^2 reportedly exhibited alterations in behavior (*@MR2325*), and rats exposed to PW 1-1.5 GHz at 0.2 and 1.4 mW/cm^2 showed disturbed motor coordination and balance (*@MR2944*). Recent experiments by D'Andrea et al (written communication, January 1979) and Lovely et al (*@MR3087*) have found transitory alterations in spontaneous and conditioned behaviors after multiple exposures of rats to 2.45 GHz at 0.5 and 5 mW/cm^2. A report by Lobanova and Goncharova (*@MR2421*) described a temporary degradation of conditioned reflex behavior in rats exposed for 1 h/d for 4 months to 69.8 MHz at 150 V/m. This frequency is in the range of maximum whole-body absorption in humans (*@MR2925*). Cleary and Wangemann (*@MR2018*) observed a decrease in drug-induced (barbiturate) sleeping time in rabbits after exposure to 2.45-GHz or 1.7-GHz radiation at

5 mW/cm^2 and above. They suggested that sleeping time was related to changes in temperature and that the effects observed were related to the rate and distribution of energy absorption.

Dumanskii and Shandala (*@MR1832*) reported alterations in spontaneous and conditioned behavior at power density levels (1.9-10 $\mu W/cm^2$) that are difficult to measure accurately. Disturbances in conditioned reflex behavior were reported by Serdiuk (*@MR2518*) after exposure of rats and rabbits to 50 MHz at field strengths of 0.5-6 V/m.

Several reports have mentioned negative results with regard to behavioral changes after RF and microwave exposure. These included rats irradiated with 3- and 10.7-GHz microwaves at 0.5-25 mW/cm^2 for 8 and 17 days (*@MR0041, @MR0139*), dogs exposed for short periods to 2.45 GHz at 88-176 mW/cm^2 (*@MR1180*), monkeys exposed to 3.2 GHz at E-field strengths of 213-736 V/m (*@MR1950*), and monkeys exposed to single doses of 2.45-GHz radiation at 16-62 mW/cm^2 (*@MR2270*). An explanation for the contradictory results with regard to behavioral effects is not clear at the present time.

(g) Cardiovascular Effects

Radiofrequency and microwave-induced effects on the cardiovascular system have been reported in animals after exposure at power densities of 10 mW/cm^2

and below (*@MR1254,@MR1747*). In these experiments, rabbits were irradiated at frequencies of 2.4 GHz and power densities of 7-12 mW/cm^2 (*@MR1254*) and at 3.0 GHz (PW) and 3-5 mW/cm^2 (average) (*@MR1747*). Changes in cardiac rate were seen, depending on which area of the animal was exposed. Similar studies (*@MR0919,@MR0447*) have failed to duplicate these results in rabbits. However, a study (*@MR1243*) using rats found evidence of bradycardia after exposure at 2.45 GHz and 30 mW/cm^2 (estimated equivalent power density). Epidemiologic studies (*@MR1081,@MR0634,@MR0084,@MR0079,@MR0287*) have noted cardiovascular anomalies in RF/microwave-exposed workers primarily involving abnormal ECG's and changes in cardiac rate. These studies have a number of deficiencies, however, including poor statistical analysis and a lack of proper controls. A study (*@MR1897*) describing direct irradiation (2.5 GHz) of the precordial regions of humans found no significant changes in cardiac function after five daily 10-minute exposures.

Related to cardiac studies are findings with regard to the effect of RF and microwave radiation on implanted electronic cardiac pacemakers (see Chapter IV for details). Microwave radiation of various frequencies interfered with the signals of some cardiac pacemakers (*@MR0600,@MR1280*), and several case histories were cited as examples of pacemaker interference by microwave ovens, TV antennas, radar, and surgical diathermy units (*@MR1203,@MR0870,@MR1280,@MR0600*). Some models of pacemakers have been found to be more susceptible than others to interference by microwave radiation (*@MR0870,@MR1203*). One method of preventing interference is to electrically shield pacemaker units

(*@MR0600,@MR1280*), and today this is a common practice in the design of such units.

(h) Hematologic Effects

Several components of blood have been reported to be sensitive to irradiation by RF and microwave energy. Epidemiologic studies have described changes in counts of WBC's (*@MR0856,@MR0857,@MR0850,@MR2667,@MR3066*), RBC's (*@MR0856,@MR0857*), and platelets (*@MR0850,@MR2667*); other studies have presented contradictory evidence (*@MR0170,@MR0569,@MR1405*). Daily's study (*@MR0569*), published in 1943, on US sailors with uncontrolled exposure to microwave radiation for various periods of time revealed no effects as measured by RBC, WBC, and differential WBC counts and hemoglobin concentration. A Polish study (*@MR0850*) reported a trend toward lymphocytosis and a moderate decrease in platelet count for workers exposed to microwave radiation for over 5 years. In addition, changes in various blood variables were reported in epidemiologic studies by Barron et al (*@MR0856,@MR0857*) involving exposure to 2- to 10-GHz radiation, but these authors presented contradictory results in a later paper (*@MR0170*). Sokolov et al (*@MR2667*) reported that workers exposed to microwaves at relatively low levels exhibited transitory, moderate decreases in levels of platelets and leukocytes.

Animal studies have indicated that changes in the blood such as in RBC and WBC counts can occur in animals exposed to frequencies in the range of

2.4-60 GHz during long periods at 10 mW/cm^2 (*@MR0016,@MR2093*), 1 or 10 mW/cm^2 (*@MR2661*), 3.5 mW/cm^2 (average) (*@MR0169*), and 3 mW/cm^2 (average) (*@MR1823*). Short-term exposure of mice to 2.95 GHz at 0.5±0.2 mW/cm^2 reportedly resulted in an increase in the mitotic index of stem cells (*@MR1605*). Ferri and Hagan (*@MR2093*) observed significant changes in RBC counts in rabbits exposed for 8-17 weeks to 2.45-GHz radiation at 10 (±3) mW/cm^2. Similar changes were not observed in WBC counts. Obukhan (*@MR1600*) reported that rats irradiated at 2.4 GHz and 0.05-0.5 mW/cm^2 for 6 hours (single and multiple exposures) exhibited alterations in bone marrow megakaryocytes. Longer periods of exposure (30 days) have resulted in changes in blood chemistry in rats irradiated at 2.4 GHz and 0.01-0.5 mW/cm^2 (*@MR3046*). Decreases in blood cholinesterase activity and leukocyte count were described by Serdiuk (*@MR2518*) after long-term exposure of rats and rabbits to 50 MHz at 0.5-6 V/m. Changes in iron transport were noted at power densities below 10 mW/cm^2 (*@MR1459,@MR1823*). Experiments performed with 24-GHz microwave energy indicated that changes in RBC and WBC counts, hemoglobin concentration, and hematocrit can be produced in certain strains of rats exposed at 10 mW/cm^2 for 3 hours (*@MR0193*). However, no significant changes in blood composition were found in a study involving exposure of rats to 2.4 GHz at 5 mW/cm^2 for 90 days (*@MR0122*).

A recent (1979), and apparently well-controlled, study by Pazderova-Vejlupkova and Josifko (*@MR3108*) showed significant decreases in hematocrit, leukocytes, and lymphocytes after long-term (7 weeks) irradiation of rats at

2.74 GHz (PW) and 24 mW/cm^2. The maximum increase in rectal temperature of irradiated animals was 0.5 C.

(i) Effects on the Immune Response

The consequences of changes in immunologic function have not been adequately addressed in terms of a potential hazard from exposure to RF and/or microwave energy. Numerous reports of RF- and/or microwave-induced effects exist, however. Effects of low levels of RF and microwave radiation on the immunologic system have been seen in experiments involving exposures of animals to radiation with frequencies of 2-3 GHz at power densities of 0.5-10 mW/cm^2 (*@MR2662,@MR0169,@MR0185,@MR1390,@MR2603,@MR0050*). Effects noted included fluctuations in phagocytic activity (*@MR1390,@MR2662*), increases in antibody-producing cells (*@MR0185*), and impairment of granulocyte function (*@MR0050*). Decreased phagocytic activity was also reported after long-term exposure of rats and rabbits to a frequency of 50 MHz at an E-field strength of 0.5-6 V/m (*@MR2518*). A study by Huang et al (*@MR1663*) reported that cells from hamsters irradiated for 5 days at 5-45 mW/cm^2 and 2.45 GHz exhibited a dose-dependent decrease in the number of mitogen-stimulated lymphocytes undergoing mitosis. Increases in lymphocyte number and nuclear disintegration in lymphoblastoid cells were reported after multiple exposures of guinea pigs to3-GHz radiation at 3.5 mW/cm^2 (*@MR2603*). Decreases in antibody titer were observed after exposure of rabbits to "SHF" radiation at power densities below 1 mW/cm^2 (*@MR0200*).

An epidemiologic study (*@MR2673*) revealed an inhibition of phagocytic activity in radio engineers and technicians exposed at radiofrequency E-field strengths above 20 V/m. The authors of this report described increases in phagocytic and bactericidal activities in rats after long-term exposure to 14.88-MHz fields at 100 V/m, however. As noted earlier, humans and rats have different absorption characteristics in this frequency range (*@MR2925*). Another epidemiologic study (*@MR3066*) described alterations in immunocompetence in workers exposed at power densities of 1 mW/cm^2 and below.

Correlation of Exposure and Carcinogenicity, Mutagenicity, Teratogenicity, and Effects on Reproduction

(a) Carcinogenicity

No strong evidence has been found that would link exposure to RF and microwave radiation to the production of cancer in humans. In a study by Prausnitz and Susskind (*@MR1251*), 21 of 60 mice that died while chronically exposed to 9.27-GHz pulsed radiation at 100 mW/cm^2 (a high dose) reportedly had developed leukemia, leukosis, or both, whereas only 4 of 40 control mice were similarly affected. However, these experiments were performed at a frequency at which most human absorption of energy would occur at the surface of the skin, and there is no reason to believe that humans would be affected in the same way as the mice in the study.

Results of an epidemiologic survey of families with mongoloid children have been reported by Sigler et al (*@MR1373*) and by Cohen and Lilienfeld (*@MR0537*). The survey findings suggested that an increased percentage of fathers who had been exposed to radar had sired mongoloid children. However, a subsequent replicative study (*@MR3024*) failed to confirm this finding. The earlier reports did not attempt to quantitate paternal microwave exposure; other variables, such as the possible exposure to ionizing radiation from microwave-generating equipment, were not examined. The authors concluded only that further study of this phenomenon was warranted.

A recently published study (*@MR3075*) analyzed health and mortality records of persons employed at the US Embassy in Moscow while microwave radiation was being beamed at the building. Embassy personnel experienced no unusual increase in cancer. Nevertheless, the authors felt that followup long-term studies were needed.

(b) Mutagenicity

Varma et al (*@MR2971*) found significant increases in mutagenicity in mice after single and multiple 10-minute exposures to 2.45-GHz radiation at 50-100 mW/cm^2. Some experiments with hamsters did not indicate that microwave exposure can produce chromosomal aberrations in vivo (*@MR1016,@MR1663*). However, one report (*@MR0121*) claimed that exposure to 23- to 24-GHz radiation at 10-500 mW/cm^2 produced an increase in the number of chromosome breaks in hamsters. In addition, in vivo exposures to 20- to 35-MHz (PW) microwave energy reportedly produced increases in abnormal mitoses and meioses. Detailed dose information was not given, however, and irradiation at 9.3-9.4 GHz failed to produce these effects. Reports have described the in vitro production of chromosomal aberrations in animal and human cells after exposure to 19- to 40-MHz pulsed radiation (*@MR0988,@MR0121,@MR0156*) and CW 2.45-GHz radiation (*@MR0013*); chromosomal aberrations have also been found in garlic root tips after exposure to 27 MHz (PW) (*@MR0987*). The production of mutations in Drosophila after 20- to 30-MHz pulsed irradiation (*@MR0988*) and in plants after 200-MHz radiation (*@MR2589*) has also been reported. However, the relevancy of such studies to humans is uncertain. Italiano et al (*@MR2615*) examined chromosomes from five radar operators and from unexposed controls. No difference between the two groups was found in the incidence of chromosomal aberrations. Studies of mutation induction in bacteria have failed to show increased mutagenicity as a result of irradiation at 1.7 or 2.45 GHz (*@MR2963*).

(c) Teratogenicity

Teratogenic and embryotoxic effects of microwaves have been reported in several animal studies, but the results were not conclusive. Bereznitskaya and Rysina (*@MR2678*) irradiated pregnant mice at 10 mW/cm^2 with 3-GHz radiation. Changes were noted in fetal death rate, average fetal weight, production of developmental anomalies, average litter size, postnatal mortality, and behavior of newly born irradiated mice. Similar results were noted by Bereznitskaya (*@MR0779*) in a study in which female mice were irradiated at 3 GHz and 10 mW/cm^2 for 5 months before and during pregnancy. However, Rioch (*@MR1273*) found no behavioral changes in progeny from pregnant rats exposed to 1.7-GHz radiation at 20-30 mW/cm^2, and Michaelson et al (*@MR0362*) found no adverse effects in progeny from pregnant rats irradiated at 2.45 GHz and 10 and 40 mW/cm^2. Similar findings were reported by Jensh et al (*@MR2574*) after irradiation at 918 MHz and 10 mW/cm^2, and normal litters and an absence of fetal abnormalities were found in a study by Miro et al (*@MR1113*) in which male and female mice and rats were exposed to PW 3.1 GHz at 8±3 mW/cm^2 for 18-306 hours and then mated with unirradiated partners. On the other hand, Shore et al (*@MR1765*) reported lowered relative body and brain weight in offspring of rats irradiated at 2.45 GHz for 5 h/d and 10 mW/cm^2 between days 3 and 19 of pregnancy, and Berman et al (*@MR1583*) found an increased incidence of cranioschisis in offspring of mice irradiated at 2.45 GHz and 3.4-28 mW/cm^2.

After irradiation of pregnant mice at much higher power density levels (estimated to be 123 mW/cm^2), Rugh et al (*@MR0043,@MR1754*) found an increase in the occurrence of developmental anomalies after irradiation at 2.45 GHz. Dietzel (*@MR1826*) reported that the number of malformations induced after irradiation of pregnant rats depended on the day of pregnancy on which exposure occurred. Dietzel et al (*@MR0625*) reported that irradiation of large numbers of pregnant rats at a frequency of 27.12 MHz at unspecified doses resulted in numerous malformations including abnormalities of the CNS, eye deformities, cleft palates, and deformation of tails.

Chernovetz et al (*@MR1996*) found no gross structural abnormalities in the progeny of pregnant rats irradiated at a frequency of 2.45 GHz and an absorbed dose of 31±3 mW/g. However, the percentage of resorbed fetuses was higher in the irradiated animals, and the average fetal mass was lower.

Other teratogenic studies have involved chicken embryos (*@MR1654*), Japanese quail embryos (*@MR0350,@MR0032*), and insect pupae (*@MR0502*). Van Ummersen (*@MR1654*) irradiated large numbers of chicken eggs at 2.45 GHz and 200-400 mW/cm^2. Embryonic abnormalities that may have been the result of heating were observed. Exposure of quail eggs at much lower power densities (30 mW/cm^2) did not result in the development of gross abnormalities (*@MR0350,@MR0032*).

(d) Effects on Reproduction

Some reports suggest potential associations between RF and microwave exposure and reproductive damage. Imrie (*@MR2377*) described three cases in which pregnant women were inadvertently given pelvic diathermy treatment in the shortwave frequency range. Two patients gave birth to normal children, but the third patient aborted approximately 1 month after her last treatment. It was possibly significant that the patient who aborted had been irradiated close to the day of expected ovulation, whereas the other two women had apparently been irradiated after the time of implantation. Another case of miscarriage after diathermy treatment was described by Rubin and Erdman (*@MR1908*). The authors noted that in other cases microwave diathermy treatment had no observable effect on ovulation or conception.

Several animal studies have involved mating irradiated males with unirradiated fertile females to determine fertility changes. In one such study, long-term (59 weeks) multiple exposures of male mice to PW 9.27 GHz at 100 mW/cm^2 resulted in increased testicular degeneration, as reported by Prausnitz and Susskind (*@MR1251*). In an earlier study involving shorter terms of exposure, Susskind (*@MR1415*) found no apparent effects on fertility in male mice exposed to near-lethal doses (124 mW/cm^2) of 9.1- to 9.2-GHz radiation. The mice either received single exposures or multiple exposures for up to 5 consecutive days. The different results obtained in these studies can apparently be attributed to the different periods of exposure used.

Testicular damage and increased numbers of stillborn progeny and debilitated progeny have been reported in mice after short- and long-term exposure to 1.7- to 3-GHz radiation at 10 mW/cm^2 (*@MR1582,@MR0054*). Bereznitskaya and Kazbekov (*@MR1582*) irradiated male mice at 3 GHz and 10 mW/cm^2 2 h/d for 5 months or longer. Microscopic examination of the testes of irradiated and control mice revealed a higher incidence of testicular degeneration in mice irradiated before birth and for 5 months after they were born. In addition, progeny from irradiated mice showed an increased incidence of "debilitation," postnatal mortality, and decreased litter size. Varma and Traboulay (*@MR0054*) found degeneration in testicular tissue in mice irradiated at 1.7 GHz and 10 mW/cm^2 for 100 minutes. Exposure at this power density level for less than 100 minutes failed to show significant testicular changes. However, alterations in spermatogenesis were observed after exposure at 50 mW/cm^2 for 30-40 minutes.

Testicular damage was also found by Gunn et al (*@MR0210*) after irradiation of rats at a relatively high power density (250 mW/cm^2). Severity of damage increased with increasing periods of exposure. Muraca et al (*@MR2366*) observed testicular degeneration in rats after exposures of 10-73 minutes to 2.45-GHz radiation at 80 mW/cm^2 ($\pm$10 mW/cm^2). Testicular damage was correlated with a rise in intratesticular temperature. Miro et al (*@MR1113*) failed to detect morphologic changes in the genital organs of mice and rats after long-term exposure to PW 3.1 GHz at 8$\pm$3 mW/cm^2. However, Dolatkowski et al (*@MR2347*) reported changes in reproductive epithelia of rabbits exposed for a total of 80 hours over 2-3 months to 3 GHz at 3 $\mu W/cm^2$. The accuracy of the measurement of this extremely low power density may be questioned. No significant reproductive effects were seen in rabbits exposed at a hundredfold greater dose (0.3 mW/cm^2) for the same period of time but at 10 GHz.

A study by Lancranjan et al (*@MR0235*) found statistically significant alterations in spermatogenesis in workers reportedly exposed to "tens to hundreds" of microwatts per square centimeter at frequencies in the range of 3.6-10 GHz. Specific effects noted included decreases in sperm count and sperm motility. Followup examinations conducted 3 months after exposure ended showed improvement in two-thirds of the exposed individuals.

Discussion

Whether the effects reported in the preceding Correlation of Exposure and Effect sections indicate potential occupational hazards or increased risk of disease is not clear. A recent study by Robinette and Silverman (*@MR3058*) of approximately 40,000 military technicians failed to detect any significant increase in disease mortality among exposed personnel. No quantitation of exposure was given, however, and the two groups of subjects studied were not compared with any other control group.

A large body of literature appears to suggest that deviations in normal biologic variables can occur after exposure to RF and microwave energy. Of particular concern are effects associated with exposure at levels of 10 mW/cm^2 and below. These include microscopic ocular changes, alterations in neuroendocrine function, changes in the CNS, behavioral changes, changes in immunologic systems, embryotoxic effects, and reproductive effects. These reports appear to indicate a potential for bioeffects that may result from actions of RF/microwave radiation other than hyperthermia. This is far from proven, however, and the issue of the induction of "nonthermal" effects remains a very controversial one.

For many of the biologic effects reported here, the extent of the effect seems to be related to the amount of energy absorbed. However, solid dose-response information is rarely available. Furthermore, in most cases existing data are not adequate to provide answers to several important questions relevant to human exposure to RF and microwave radiation. Some of these questions follow: (1) Are the reported bioeffects cumulative, and do thresholds exist? (2) Are the effects reported frequency dependent? (3) Are there consistent differences between CW and PW radiation with regard to the induction of an effect? (4) For PW radiation, are pulse rate and pulse duration significant factors in inducing an effect? (5) How valid is the extrapolation from animal data to humans?

The answers to these and other questions cannot be provided from the present body of literature. Further research is needed in the various areas of concern. Pending the resolution of these problems, a cautious approach should be taken in regulating human exposure to RF and microwave radiation, and conservative exposure limits are warranted.

IV. INTERFERENCE AND OTHER PHYSICAL PROCESSES THAT AFFECT BIOLOGIC ACTIVITY

During the 1940's and 1950's, biologically inert metals gained widespread use for various medical and surgical functions. For example, implants such as plates, pins, cups, and joints replaced degenerated portions of the human skeleton, and wire or staples were used as surgical sutures. In recent years, plastic or elastomeric materials have supplanted metals for many uses; nevertheless, some portion of the general populace (and, therefore, of the work force) still carries metal implants.

These biologically inert metals are not electrically inert; they can serve as conductors, as opposed to insulators or dielectrics, of electromagnetic fields and can induce heating in tissues due to their resistive properties. The localized heating that may occur within the body when humans or other animals containing metal implants enter an electromagnetic field can then lead to localized tissue destruction. For this reason, mention should be made of the interaction of metal implants with RF and microwave energy and the interaction of that energized implant with the tissues, if only to advise employers that exposure of employees bearing metallic implants to RF and microwave energy deserves special attention and, perhaps, extra caution.

Available reports on the effect of implanted metals on the field distribution within the body are limited to studies on diathermic applications. Ducker (*@MR2284*), in 1968, presented results of model studies on heating patterns produced by metals of varied shapes. Electric fields were generated by two disk-shaped diathermy applicators, and the metals were embedded in a 2% agar solution. According to Ducker, the metals acted as shunts, ie, pathways of low resistance with respect to the surrounding tissues, and did not heat up. Rather, the solution overheated near the metal-medium interfaces closest to the disk applicators.

Using several dogs and a cat into which tantalum, silver, and stainless steel had been implanted, Etter et al (*@MR0669*), in 1947, concluded that no adverse heating occurred during diathermic treatment in tissues contiguous to the implants. Temperature measurements were made with nonmetallic thermometers near skull plates, cuffs around the sciatic nerve, intramuscular plates, subcutaneous and epineurial foil, and subcutaneous wire during 20-40 minutes of irradiation with 14.25-, 15.75-, 33.2-, and 37.5-MHz shortwaves. All but the first implant were placed in one femur; the other femur served as a control. Although temperature differences were noted between femurs with and without the implant, they were not significant. Microscopic examination of the tissues revealed no differences between the two femurs. Although blood circulation reportedly was not impaired, all animals were anesthetized before diathermy.

In a companion study, Lion (*@MR1209*) described results of similar experiments performed with models. The metal implants were inserted into electrolyte solutions and irradiated with the same diathermy applicators used by Etter et al at frequencies of 10-55 MHz. Visible indicators of thermogenesis, such as silver iodide crystals, raw meat, albumin, or egg white solutions, were used to determine the field distribution around the metal implant. In all cases, deformation of the field and local evidence of heating were observed. Lion attributed conduction of the heat generated by irradiation away from the implant as responsible for the lack of heating observed by Etter et al and, thus, suggested that the deformation of the field by the implant was of little practical significance to the animal. He also noted that Etter et al may have implanted the metals too deeply within the body to permit a large temperature increase.

Experiments using liver tissue in vitro were discussed by Feucht et al (*@MR0684*) in 1949. Stainless steel plates of varying sizes were imbedded at one of two depths, and the tissue was irradiated for 10 minutes with 2.45-GHz microwaves. Temperature increases were greater in the region between the implanted metal plate and the tissue surface when the implant was 0.5 cm vs 2.0 cm from the surface. The differences were approximately 40 C over the range in depths from 0 to 0.5 cm. The formation of standing waves between the applicator and the implant close to the tissue surface was hypothesized to account for this increased heating. When plates were implanted in the abdominal walls of rabbits, temperature increases were also observed following irradiation. These were only 3-5 C greater than control (without implants) values and some 35 C less than the increases produced in vitro. Coagulation and edema were observed, however. Blood circulation and reflections from the abdominal wall kept the amount of the temperature increase with in vivo diathermy treatment small, according to Feucht et al. .

No adverse effects due to diathermy treatment of rats containing tantalum implants were reported by Smith (*@MR1383*) in 1950. Long-wave diathermy, in which small localized areas of tissue are heated by currents, was compared with shortwave diathermy, in which the body serves as a dielectric between two capacitor plates or in which a coil similar to that found in an induction furnace is used. No temperature rise or effects on the tissue were observed. The presence of stainless steel wire sutures did not lead to microscopically observable tissue damage in the lumbar region of dogs treated with 17.12-MHz shortwaves, according to a 1961 report by Hewett et al (*@MR2359*).

Although all these reports seem to indicate that metal implants should not place their bearers in any danger of harm (heating) from RF and microwave irradiation, their results are controverted by the lack of quantitative dosimetry of the incident field. Knowledge of the ouput power, eg, 62.5 W in one report (*@MR0684*), was of no use in determining the exposure conditions. The only observation that reliably can be made is that localized heating can occur near metal implants. The degree of this heating and its potential ability to cause macroscopic damage to cells and tissues cannot be estimated now, and the existence of nonthermal effects due to deformation and concentration of the incident field by the implant can only be surmised.

Also of concern are implanted electronic cardiac pacemakers. As discussed by Ruggera and Elder (*@MR0408*) in 1971, such pacemakers can be susceptible to interference from electromagnetic radiation in the microwave frequency range. A more recent report, published in 1976 by Mitchell and Hurt (*@MR0359*), analyzed the effects of RF and microwave energy on 23 pacemaker models. The results showed that electromagnetic interference depends strongly on frequency, pulse width, pulse repetition rate, E-field strength, and field polarization. Protective shielding reportedly was a major factor in preventing or reducing interference; improved shielding had been incorporated in the design of many of the pacemaker models tested.

Lichter et al (*@MR1203*), in 1965, cited the case histories of two 68-year-old men who, at the time of electronic cardiac pacemaker implantation, were exposed to RF/microwave energy from surgical diathermy units that were being used during thoracotomy to suture implantable pacemaker leads to the myocardium. During the implant procedure, the heart was paced by an external cardiac pacemaker. In the first patient, when the pericardium was cut with the active electrode of the diathermy unit, the normal "pip" of the pacemaker speaker became a "buzz" and ventricular fibrillation ensued. Similar events took place in the second case, with fibrillation occurring almost immediately after diathermy application.

According to King et al (*@MR0870*) in 1970, a 68-year-old man with an implanted electronic pacemaker lost consciousness while near an operating microwave oven in a restaurant. In the hospital, he was intentionally placed 1.5 m from a microwave oven. When the oven was turned on, the ECG recording showed a blocking of pacemaker activity believed to be due to the microwave radiation. Temporary fainting symptoms were subsequently experienced by the patient. Three other patients with implanted electronic cardiac pacemakers were similarly exposed to microwave energy from a microwave oven that operated at 2.45 GHz. A patient with the same type of electronic cardiac pacemaker as the first patient demonstrated a loss of the pacemaker signal. Different models implanted in two other patients were not affected.

In 1973, D'Cunha et al (*@MR0600*) cited the case history of a 62-year-old man with an electronic cardiac pacemaker who began experiencing attacks of vertigo and faintness and, during a 6-month period, lost consciousness on six occasions. All of the subject's attacks occurred in a parking lot near his place of work located near a UHF television transmitter. Measurements in the parking lot where the fainting incidents occurred revealed field strengths of at least 0.5 V/m at a frequency of 492 MHz. The distance between the TV antenna and the parking area was roughly 259 m. When a shielded electronic pacemaker was implanted into the patient, the interference experienced in the parking lot ceased and further fainting episodes were prevented.

Hunyor et al (*@MR0863*), in 1971, described the effects of various electric and microwave-producing devices on three patients with the same type of implanted electronic cardiac pacemaker. Times of exposure and power densities were not given. A microwave generator producing microwave energy at 2.45 GHz was aimed at various body parts, including the area containing the pacemaker. A physiotherapy diathermy unit operating at 27.12 MHz was tested at various distances (not given) from the patients and also when touching the patients' knees. Finally, patients were exposed at 5, 3, and 1 m from, and next to, a microwave oven with a frequency of 2.45 GHz. The door of the oven was opened frequently during irradiation. According to the authors, this allows "puffs" of microwave radiation to escape. Neither the oven nor the generator produced ECG changes in any of the patients. The physiotherapy diathermy unit, when placed directly on the knees, caused the rate of the pacemakers of two patients to increase to 136 beats/min. When not in direct contact with the patients, the diathermy unit had no effect on the pacemakers.

In a 1975 experiment by Rohl et al (*@MR1280*), electronic cardiac pacemakers were implanted in dogs and humans. The humans and animals were placed 1.2 km from a radar antenna, which operated at PW 1.3 GHz (400 pps, 5 μs) and revolved once every 5.5 seconds. Exposure was reportedly at 3.5 mW/cm^2; however, no duration of exposure was given. When exposed, only one of four unshielded, implanted pacemakers was not inhibited or triggered. Two implanted pacemakers that were shielded were not affected.

Lichter et al (*@MR1203*), in 1965, reported the results of diathermy irradiation on a number of anesthetized sheep and dogs (exact number not given) connected to various external electronic cardiac pacemakers. All animals underwent chest surgery, during which a surgical diathermy unit was employed. The surgical diathermy units operated at various frequencies between 500 kHz and 2.5 GHz, eg, 27 MHz. Immediately or a short time after the diathermy unit was brought near or used on the animals, ventricular fibrillation was noted in animals implanted with either of two different pacemaker models. Fibrillation occurred when the active needlepoint electrode touched tissue or when it was placed near these animals. Fibrillation was not produced in two similar experiments in which different models of pacemakers were used. In another experiment, a sheep was implanted with one of the RF-sensitive pacemakers and irradiated by a unipolar microwave generator at 2.43-GHz and 125-W output power. Fibrillation did not result from exposure at this higher frequency.

The effects of far-field CW and PW 3.05-GHz radiation on five models of electronic cardiac pacemakers surgically implanted in dogs were described in 1972 by Hurt (*@MR0864*). Exposures took place in an anechoic chamber at least 2 weeks after implantation. Duration of exposure was not given. In one pacemaker, CW radiation at 32.5 mW/cm^2 caused a slight decrease in beats per minute. One model was not affected in any of the trials. Pulsed-wave microwave energy (pulse duration 3 µs - 5 ms) generally caused an increase in beats per minute as the number of pulses per second was lowered from 400 to 18. In some models, an increase in power density caused a conversion from baseline rate to fixed rate, or a decrease in beats per minute. Changing the pulse duration also produced changes in the rate of the electronic cardiac pacemaker.

Rustan et al (*@MR0044*), in 1973, reported findings on nine anesthetized dogs that were implanted with different models of electronic cardiac pacemakers and irradiated at 2.45 GHz. The animals were placed in an anechoic chamber and irradiated in the far-field region at from approximately 0.8 $\mu W/cm^2$ to more than 100 $\mu W/cm^2$. Electrocardiographic tracings from all nine animals were made both before and during irradiation to monitor any change in heart rate. Four pacemakers ceased to function during irradiation. Two stopped at 8 $\mu W/cm^2$, one at 50 $\mu W/cm^2$, and the other at almost 130 $\mu W/cm^2$. Changes in heart rate, both increases and decreases, were found in two dogs during irradiation.