

Effects of Exposure to Microwaves: Problems and Perspectives*

by

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During the last 25 years, there has been a remarkable development and increase in the number of processes and devices that utilize or emit microwaves. Such devices are used in all sectors of our society for military, industrial, telecommunications, and consumer applications. Although there is information on biologic effects and potential hazard to man from exposure to microwaves, considerable confusion and misinformation has permeated not only the public press but also some scientific and technical publications. The purpose of this review is to place the available information on biologic effects of microwaves in proper perspective and to suggest approaches to future studies.

Introduction

Elucidation of the biologic effects of microwave exposure demands a careful review and critical analysis of the available literature. Such review requires an appreciation of past scientific achievements as well as differentiation of the established effects and mechanisms from

speculative and unsubstantiated reports. Although most of the experimental data support the concept that the effects of microwave exposure are primarily, if not only, a response to hyperthermia or altered thermal gradients in the body, there are large areas of confusion, uncertainty, and actual misinformation.

In order to provide proper perspective in the analysis of the literature on the biologic effects of microwave exposure, it is helpful to delineate the information into categories: (a) biophysical (primary events—absorption, reflection, scattering, heat sources, and molecular and cellular biology); (b) biomedical (pathophysiologic manifestations in experimental animals); and (c) clinical response of man.

Biophysical Principles

To provide a basis for understanding the biologic effects of microwaves, review of some fundamental aspects of electromagnetic radiation is indicated. The nonionizing electromagnetic (EM) spectrum encompasses wave-

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lengths from 3×10^8 m to 3×10^{-2} nm (Fig. 1) (1). The radio frequency (rf) portion of the EM spectrum extends from 0.03 MHz (very low frequency, VLF) to 300,000 MHz (extremely high frequency, EHF). On a functional or operational basis, frequencies in the region from 100 MHz to 300,000 MHz (300 GHz) are designated microwaves.

One quantum of microwave energy is approximately 10^{-5} electron volts (eV), which is much too low to produce the type of excitation necessary for ionization, no matter how many quanta are absorbed. It has been determined that one ionization occurs on the average for

every 34 eV of energy expended in air. The actual amount of energy needed to eject an electron from a molecule (ionization potential) ranges from 10 to 25 eV (2). The extra energy which is expended is used to form excited molecules. Where large molecules are involved, the energy is distributed through the entire molecule with too little energy concentrated at any one bond to cause its rupture. The energy is removed from the system as oscillation energy which becomes randomized and is converted to heat.

In biological systems absorbed microwave energy is transformed into increased kinetic

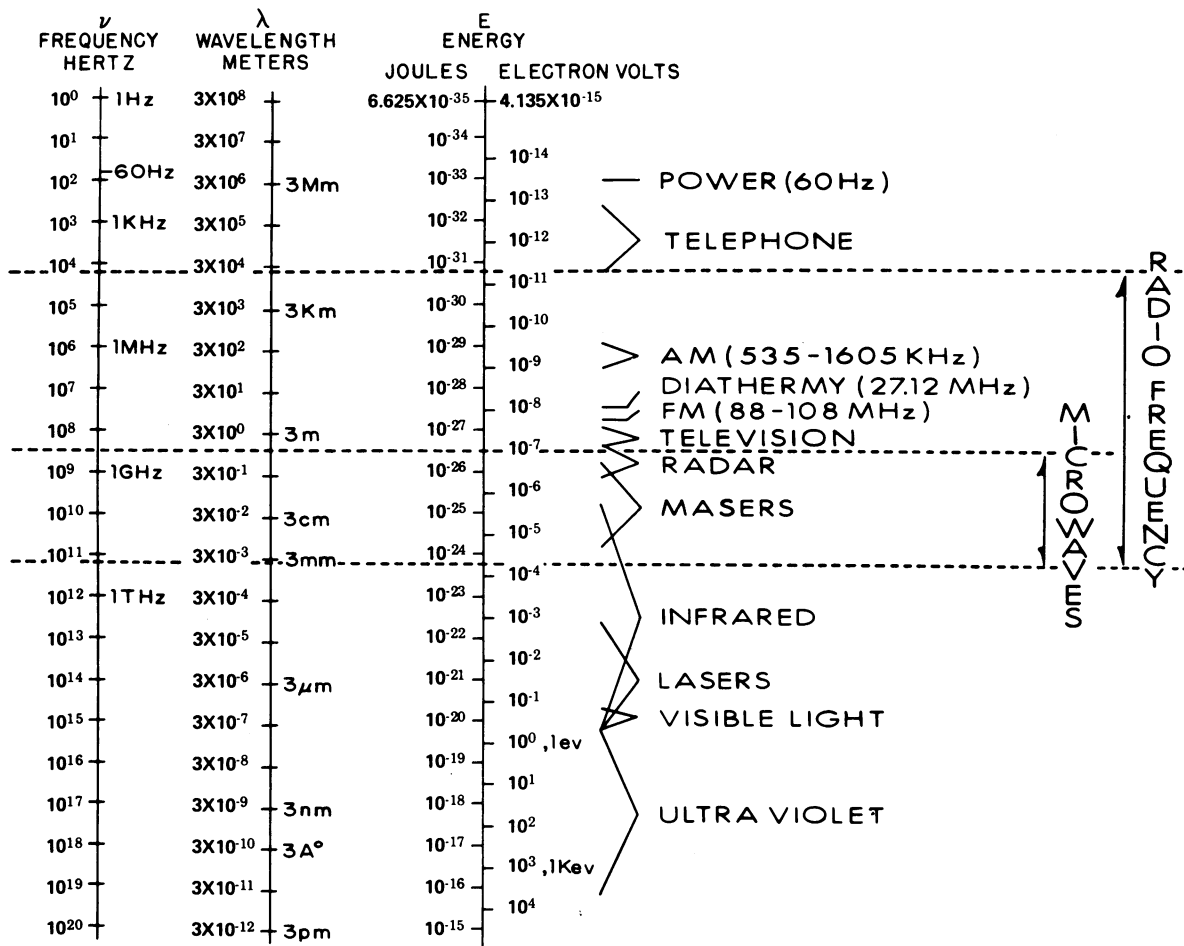


FIGURE 1. Nonionizing electromagnetic radiation. Adapted from Air Force Manual AFM 161-8, 1969.

energy of the absorbing molecules, thereby producing a general heating of the tissue. Such heating results from both ionic conduction and vibration of the dipole molecules of water and proteins (3). The absorption of microwaves is dependent upon the electrical properties of the absorbing medium, specifically, its dielectric constant and electrical conductivity. These properties change as the frequency of the applied electric field changes. Values of dielectric constant and electrical conductivity and depth of penetration have been determined for many tissues (4).

The absorption coefficient and depth of penetration of microwaves in tissues appear to be an inverse function of the wavelength. The dielectric constant and specific resistance of tissues are essential material constants which determine the development of heat in tissue. The dielectric constants and specific resistances of different tissues are known and can be used to calculate penetration depths (4, 5). Tissue with a low water content such as fat is penetrated by microwaves to a considerably larger extent than muscle with a high water content. In each case, the depth of penetration decreases rapidly with increasing frequency. For example, the wavelength of 2500 MHz provides a depth of penetration of about 9 mm in muscle. For a frequency of about 900 MHz, the depth of penetration is double that attained with 2500 MHz. The comparatively high depth of penetration in fatty tissue seems to indicate an ability of the energy to penetrate the subcutaneous fat without major energy loss and thereby becomes available for heat transfer in the deep tissues. This would only be true if all the energy which reaches the muscular and other deep tissues would be absorbed by them. Partial reflection of electromagnetic waves will occur at the interface separating different media. The relative amount of the total energy which will be reflected is determined by the dielectric constants and specific resistance values of the different media (6).

The total distribution of heat sources in the skin-subcutaneous fat-muscle complex and by summation, total heat inputs in skin, fat and muscle, have been determined by Schwan and Li (4, 5). Under the simplifying assumption that

the energy strikes at right angles to the surface of the body, at frequencies lower than 1000 MHz, most of the energy reaches the deeply situated tissues. The percentage of absorbed energy is nearly independent of skin and subcutaneous thickness and is about 40% of the airborne energy. Between 1000 and 3000 MHz, transition from deep heating to surface heating takes place; 20-100% of the airborne energy may be absorbed by the body depending on the thickness of skin and subcutaneous fat. For frequencies above 3000 MHz, most of the radiant energy is absorbed by the skin. Thus, depth of penetration becomes so small above 3000 MHz that heat conduction rather than true penetration of the energy determines deep tissue temperature to a great extent.

The biologic factors in temperature increase are mainly those related to the ability of the tissue to rid itself of excess heat. Heat transfer at a given body temperature is equal to the summation of the heat generation due to metabolic processes and heat loss from radiation and breathing. When heat loss predominates, normal temperature is restored. If, on the other hand, heat gain exceeds heat loss, the body temperature will rise.

Although thermal effects of microwave absorption have been well demonstrated and documented, some investigators suggest non-thermal or specific effects due to microwave exposure. Evidence presented for a nonthermal effect has generally been in one of several areas; microscopic, biochemical, and neurological.

Schwan and associates (6-9) have extensively studied and reviewed various aspects of nonthermal interactions of microwaves from a consideration of field-force effects, excitation of biological membranes, and macro-molecular resonances. Field-induced force effects relate to forces which are evoked by alternating electrical fields, acting on blood corpuscles, protein molecules, etc. It is well established that dc electrical fields can evoke forces acting on particles (9). Field-induced force effects can be characterized as the force of an electrical field on a real or induced charge. To date, field-induced force effects constitute the only demonstrated mechanism of nonthermal interaction of electrical fields with biological materials but they

are of no significance in the mammalian organism, since they "are always swamped by thermal effects" (10).

The phenomenon of pearl-chain formation, which has been alleged to be indicative of non-thermal effects of microwaves is discussed by several investigators (7, 11). In considering non-thermal effects of microwaves, the excellent study by Sher (11) should be noted. He concluded that the implications for pearl-chain formation are that on no account can biological pearl-chain formation occur for particles smaller than 3μ (diameter) without risking overheating of the tissues. Freely moveable particles of this size are not available in the body. It can be said with certainty that pearl-chain formation will not occur due to microwave exposure by pulsed or continuous wave (CW) of individuals observing the thermal tolerance threshold. In discussing the study by Heller (12) on the effect of electromagnetic fields on unicellular organisms which is often cited as an example of non-thermal interaction, Schwan (7) states that this orientation is caused by "the change in potential electric energy which occurs if a non-spherical particle is turned with reference to the applied field."

Roth (13), in his extensive and critical review, states: "The possibility of nonthermal effects has been the subject of much interest. However, a review of the literature, which claims the existence of such effects, fails to be quantitatively convincing. . . More research, especially conducted from a more quantitative point of view, is needed to clarify this point. . . No specific biological effects can be deduced. . . nonthermal effects quoted in the Soviet and American literature are biologically interesting but have never been clearly shown to be related to symptoms in man."

Schwan (14), in reviewing possible mechanisms of nonthermal effects, comes to the conclusion that there is little physical basis for such effects except under conditions where there is substantial average power density as well as peak levels of exposure. Most of the reports that pertain to nonthermal mechanisms of microwaves are of questionable value. Many studies are not reproducible, and the data reported are not convincing; the handling of con-

trols and the statistical analyses are inadequate; and the dosimetry employed leaves much to be desired or does not necessarily demonstrate exclusion of significant thermal increases.

Of interest in this context is the recommendation made at the international Symposium on Biologic Effects and Health Hazards of Microwave Radiation, Warsaw, Poland, October 15-18, 1973. Microwave biologic effects may be divided into three categories: high average intensities (>10 mW/cm²) at which distinct thermal effects, in some instances hazardous, predominate; the range below 1 mW/cm² in which gross thermal effects are improbable; the range of intermediate or subtle effects, about 1-10 mW/cm², in which weak thermal but noticeable effects occur as well as direct field effects and perhaps other effects of a microscopic or macroscopic nature, the details of which are at present unclarified. The border limits of these regions are approximate and may differ for various species of animals and may also depend on a variety of parameters such as frequency and modulation.

Extensive investigations into microwave bioeffects conclusively show that for frequencies between 200 and 24,500 MHz, exposure to power density greater than 100 mW/cm² for 1 hr or more could have pathophysiologic manifestations of a thermal nature. At power densities less than 100 mW/cm², however, evidence of pathologic change is nonexistent or equivocal. According to the best evidence available, the most important, if not the only, effect of microwave absorption in the mammal is the conversion of the absorbed energy into heat. Whole-body exposure of various species of animals to microwaves at levels greater than 10 mW/cm² is characterized by a temperature rise which could exceed the thermal regulatory processes of the animal. The end result is either a reversible or irreversible change depending on the conditions of the exposure and the physiologic state of the animal (15). Smaller animals show a greater temperature response than do larger animals at equivalent exposures (16).

Although there are many interesting and controversial areas that can be discussed, only literature pertaining to the eye, reproductive organs, and central nervous system will be

presented. For more detailed discussion of these and other aspects of microwave bioeffects, reviews by the author and his associates should be consulted (15-29).

Effects on the Ocular Lens

Microwaves have been shown to produce lens opacity in some experimental animals, notably rabbits (30-36). Microwave-induced cataracts have also been reported in man (37-43).

In several studies, exposure of animals to various frequencies ranging from 200-5500 MHz at field intensities up to 150 mW/cm² did not produce eye damage; most of these were whole-body exposures (44-47). Lubin et al. (48) reported that lens changes did not occur in rabbits given 400 MHz whole-body exposure even if radiation times were extended to the lethal period. Addington et al. (44) did not find any eye changes in guinea pigs, dogs, sheep, or mice, from chronic whole-body exposures to 200 MHz (CW).

Osborne and Frederick (49) exposed the eyes of dogs in seven "acute" experiments over a 3 wk period to an estimated power density of 350 mW/cm² to 470 mW/cm² (2450 MHz) for 20 min each time. There was no evidence of damage to the eyes or contiguous tissue of any of the dogs.

Daily et al. (33), using 2450 MHz, exposed the eyes of two dogs every other day, six to ten times, respectively, to an estimated power density of 300 mW/cm² for 30 min. These animals failed to show any ocular damage, ophthalmoscopically or pathologically. Eight exposures of the eye of one dog once daily for 30 min to 460 mW/cm² (estimated) produced ophthalmoscopically observable anterior cortical cataract within 6 days after the last exposure.

Whole-body exposure of dogs to 2800 MHz (pulsed) microwaves at a power density of 165 mW/cm² for 3 hr in a single exposure or as much as 6 hr daily over a 3 wk period did not produce any lenticular changes when eyes were examined regularly for several years after irradiation (47). In another report, dogs were exposed to 1280 MHz pulsed at 20, 50, or 100 mW/cm², 6 hr each day, 5 days/week for periods ranging from 2 to 4 weeks. Dogs were also exposed to 24,000 MHz pulsed, 6 hr 40 min/day, 5 days/week or 16.5 hr/-

day, 4 days/week for 20 months. Periodic examination, for 12 mo after cessation of exposure, by direct and indirect ophthalmoscopy and slit lamp did not reveal abnormalities of the lens or retina (50). In these exposures, the dogs could move around in their cages, and their eyes were not exposed directly at all times as is the case for most other investigations of microwave-induced cataracts.

Single or fractionated exposure of the eyes directly to 2800 MHz (pulsed) microwaves, 350 mW/cm² for 20 min did not result in permanent lenticular alteration in dogs. Exposure of the eyes directly to 700 mW/cm² of 2800 MHz pulsed microwaves for 20 min (single or fractionated) resulted in lens opacification involving the posterior lens capsule and posterior subcapsular cortex (51).

Carpenter and his associates (31, 32) have reported that single or repeated exposures of rabbits' eyes with 2450 MHz pulsed or CW can cause opacity when the lens temperature increases 4°C. These authors have suggested a "cumulative" effect on the lens from repeated exposures of rabbits' eyes to power densities of 120 mW/cm² or more, based on measurement of the field with a more accurate instrument than in the original report (52).

In order not to confuse this suggested "cumulative" effect with that recognized for ionizing radiation, it is important to define the cumulative effect produced by ionizing radiation to put this point in its proper perspective. Cumulative injury from exposure to ionizing radiation is a manifestation of the irreparability of a certain fraction of the injury which has been designated as residual radiation injury. Such residual radiation injury is additive with frequency of exposures and is not dependent on intervals between exposures once the full recovery potential has been realized (53). A cumulative effect is the accumulation of damage resulting from repeated exposures each of which is individually capable of producing some degree of damage. Careful analysis of the work of Carpenter et al. (31; 32), as well as Williams et al. (36) and Birenbaum et al. (30) reveals that whenever lens opacity is produced in animals, a threshold (>100 mW/cm²; >1 hr) becomes obvious. No one

has yet been able to produce cataracts even by repetitive exposures when the power density is really below threshold. Apparently the age of the animal has no bearing on the latent period for opacity induction, and there is no significant relationship between the age of the animal and the susceptibility of its lens to damage by microwave exposure (54).

Most investigators point out that there is a critical intraocular temperature which must be reached before opacities develop. This temperature ranges from 45 to 55°C. Obviously, no cumulative rise in temperature can occur if the intervals between exposures exceed the time required for the tissue to return to normal temperature. The cumulative effect to be anticipated, therefore, is the accumulation of damage resulting from repeated exposures each of which is individually capable of producing some degree of damage (55). Acute injury of the lens leads first to hydration, and this is reversible providing no lens protein denaturation has taken place despite the fact that banding, striations, and opacification are evident. Hydration of lens fibers may last for many days. If the excess water leaves the lens before denaturation has occurred, no permanent residua result. If another thermal injury intervenes, however, at a time when the lens is partially damaged, there may be a summation of effects (56). Some of the experimental lenticular opacities or cataracts may simply be due to tumescence of the lens fibers and is a reversible change. The mechanism responsible for microwave cataractogenesis is believed to be mainly a thermal one in which the maximum heating effect is produced adjacent to or within the epithelial layer of the lens (57, 58). Microwave-induced opacities in the posterior cortex may result as an interface effect at lens cortex-posterior capsule boundary or at capsule-vitreous body boundary, with concentration of the energy in the posterior cortex from reflection of microwaves. Thus the temperature could be higher in the cortex than in the vitreous body immediately behind the lens where ocular temperatures are usually recorded.

Over the past two decades, controversy and confusion has developed concerning the sensi-

tivity of the ocular lens to microwave exposure. It is incumbent upon us, therefore, to develop some rational and objective approaches to the assessment of the essential features of this controversy and misunderstanding. A considerable body of data has evolved since World War II which should permit us to put some perspective into this problem. In animal studies, the techniques used and interpretation of results and conclusions are quite often equivocal. Careful review of the reports on human cataractogenesis indicates that there has been insufficient quantitation and correlation of pathophysiology with the level of microwave exposure. It is important to note that lens opacity has consistently been produced in only one species, namely the rabbit. One can question whether the rabbit is the most appropriate animal model. According to Cogan et al. (38), with local microwave exposure the cataractogenic level for monkeys has been found to be higher than for rabbits. One has, therefore, to look at the problem from the point of view of experimental procedures, a critical analysis of the studies, as well as review and analysis of the reported human data.

Effects on the Gonads

The effects of microwave on the testes has been studied by several investigators (45, 59-61). Exposure of the scrotal area at high power densities (>250 mW/cm²) results in varying degrees of testicular damage such as edema, enlargement of the testis, atrophy, fibrosis, and coagulation necrosis of seminiferous tubules in rats, rabbits, or dogs exposed to 2450, 3000, 10,000, or 24,000 MHz.

Ely et al. (45), using 2880 MHz, tried to determine the lowest power density which would produce minimal changes in the most sensitive animal in a group of dogs. They found 5 mW/cm² to be the "threshold" for testicular damage, for an indefinite exposure. The field intensity required to maintain a threshold temperature was chosen from the most sensitive of the 35 dogs exposed. The threshold temperature of 37°C was the lowest damaging temperature found in this study. As this report has confused many reviewers who

have taken the results out of context and suggested the extreme sensitivity of the testes, it should be noted that this is based on a single animal, and the conclusion may be spurious. Not enough controls were used. Also, there may have been a normal incidence of histologic damage in unexposed animals. The authors themselves point out that the damage observed at such low power levels is slight, almost certainly fully recoverable, and the response of the testes to heating from a radar source is similar to that from other sources of heat. The same effect, which is reversible, can also be caused by a hot bath or constrictive clothing and should therefore not be considered hazardous. It is questionable, therefore, whether such effects should be legitimately considered as a basis for appraisal of hazard from microwave exposure (55).

Whole-body exposure of dogs to 24,000 MHz (62) or guinea pigs to 3000 MHz (63) did not affect reproduction. Exposure to 3000 MHz, 8 mW/cm² did not affect mating of mice or rats (64).

Gorodetskaya (65) has reported exposure of 2-3-month-old mice to 10,000 MHz, 400 mW/cm² for 5 min caused a decrease in the number of estral cycles with increase in duration of individual cycle stages. One month after exposure, the estral pattern was re-established. Mating of normal females and microwave irradiated males resulted in a decrease in number of progeny, lower average weight of offspring, and increase in number of stillborn. When mated with normals, microwave-treated females produced weaker offspring than did similarly treated males. Deformed offspring were observed only from microwave-exposed females. Histologic studies revealed degenerative changes in the germinal epithelium. In the ovaries, follicular epithelial cells were degenerated with pyknotic nuclei. The high power density (400 mW/cm²) used in this study is extreme.

Timeskova (66) studied the influence of microwaves on testicular function, impregnation, the course of pregnancy, and the offspring of sexually mature rabbits subjected to whole-body irradiation with centimeter microwaves at 100 mW/cm² with an exposure time of 15

min. Their rectal temperatures rose by 3-4°C. It was found in these experiments that the granulosa cells in the mature and maturing follicles of the rabbits degenerated and decomposed. The irradiated females were difficult to mate and were impregnated only after 6 or even 10 days with the male. It should be pointed out that 100 mW/cm² is an unrealistically high power density and will no doubt cause such effects by the extreme thermogenesis.

Although there are some experimental data to indicate that high power densities can affect the testes and ovary, it is apparent that these responses are a result of the heat which develops in the animal. The experimental evidence tends to support the conclusion that the effects of microwave radiation on the gonads are primarily of thermal origin as a result of high power density exposure.

There is no direct or confirmed evidence of genetic effects due to exposure to radio-frequency (rf) or microwaves. Heller and Teixeira-Pinto (67) have reported formation of chromosome abnormalities in plant cells and induction of chromosome aberrations in mammalian cells such as cultured human lymphocytes and in Chinese hamster lung cultures. These studies have been criticized by several investigators who noted that the authors do not offer any reliable data to support their conclusion. These authors (67) have attributed their findings to subthermal or nonthermal interactions between the energy and the biological system. Much of the work has been criticized by those who feel that the systems were subjected to a thermal stress, and these experiments have not yet been independently replicated (68). It is quite possible that the chosen parameters of the applied field caused biologically significant field-induced force effects (7). Although the authors described their results as nonthermal, no description is given of the methods of measuring the temperature. This is a particularly important omission. (55).

Janes et al (69) have reported an increased frequency of chromosome stickiness in cells obtained from bone marrow of Chinese hamsters 3, 4.75, and 5 hr after exposure to 2450

MHz. There are, however, a number of factors which make this conclusion suspect. The animals were irradiated in a field of unknown intensity which caused 46% mortality with the mean time of death being only 15.4 min and the mean rectal temperature rise of the survivors 7.5°F. These facts indicate that a high power density, probably 100 mW/cm² or more, was used.

In regard to the use of chromosomal aberrations as an indication of genetic damage, Savage (70) points out that qualitative studies are valid provided that observation is not confined to any one test system, and care is taken to ensure that aberrations observed are not the result of the experimental method employed. According to McLees and Finch (68) and McLees, Finch, and Albright (71), no *in vivo* investigations of the effect of radiofrequency or microwaves on mammalian chromosomes have been conducted at power levels sufficiently low to avoid heating the animal.

Neural Effects

The suggestion that microwaves may interact with the central nervous system (CNS) by some mechanism other than heating has been made by several investigators, mostly in East European countries, who stress that the CNS must be considered as being moderately or highly sensitive to rf or microwave energy absorption (72-78). Although some Eastern European investigators describe the thermal nature of microwaves, the majority stress non-thermal or specific microwave effects at the molecular and cellular level.

The first report on the effects of microwaves on conditional response activity of experimental animals was made by Gordon (79). In subsequent years, the study of the "non-thermal" effects of microwaves gradually occupied the central role in electrophysiological studies in the Soviet Union (80).

A considerable body of literature has grown in the USSR on transient functional changes following "low-dose" 10 mW/cm² microwave irradiation studied by investigations of changes in conditional responses. Soviet investigators have stressed that the central nervous system

is highly sensitive to all modes of radiation exposures. Their conceptual approach is based to a large extent on Pavlovian methods (81) and the principle of nervism which constitutes one of the most important theoretical bases for Soviet medicine in general.*

Several investigators have reported that rf or microwave exposure produces alterations in the electroencephalogram (EEG) (82-86). Stimulation is often followed by increased amplitude and decreased frequency of EEG components, or by decreased amplitude and increased frequency. In reviewing the literature on EEG effects, one has to be aware of certain deficiencies in this methodology. There is not always a one-to-one correspondence between functional state and character of EEG recording, which may lead to mistaken interpretation of the functional consequences of changes in the character of spontaneous activity as the result of exposure to microwaves. Spontaneous activity is very easy to measure, but extremely difficult to interpret (87).

Conditional response studies have indicated some alteration in learning as a consequence of rf or microwave exposure (88-90). Retrograde amnesia and depressed learning have been described in rats exposed to microwaves (91, 92).

The field intensity in these studies was evidently sufficiently high to result in increased body temperature. Behavioral effects, nevertheless, have also been demonstrated with apparently low intensity fields according to one group of investigators (93); more precise power density measurements, however, revealed thermally significant levels in this study (94).

Justesen and King (95) studied the behavioral effects in rats exposed to 2450 MHz at average power densities approximating 2.5, 5.0, 10, or 15 mW/cm². The temperature data con-

*It should be pointed out, however, that although the nervism principle of Sečenov and Pavlov does constitute one of the most important theoretical bases for Soviet medicine in general, specific studies are based on the theoretical foundation of the special scientific discipline within the framework of which a given effect is being studied, i.e., encephalography, biochemistry, cardiovascular pathophysiology (personal communication from Professor Z. V. Gordon to the author).

firmed an impression "growing from earlier behavioral observations that the rat is not only highly variable in its individual thermoregulatory capability but responds differentially to normal and microwave heating." In essence, these authors found "no chronic ill effects behaviorally or neurohistologically to derive from fairly long-term intermittent exposures approximating 2.5 to 15 mW/cm²; although some striking acute effects were observed, none of them was or is incompatible with the supposition that thermalization was the only consequence of irradiation."

In the context of behavioral effects, it should be noted that behavior is not a simple process and that behavioral effects may represent the summation of different effects in different systems.

Many investigators do not accept the possibility of nonthermal neural stimulation by microwaves and explain these effects entirely upon local heating (96-98). They suggest that thermal stimulation of the peripheral nerves could produce the neurophysiological and behavioral changes that have been reported. Microwaves may have a biological effect at field intensities which do not produce measurable colonic temperature changes, but altered thermal gradients or specific heat loci could affect neural responses. Changes in the functions of the nervous system produced by microwaves may not be specific (75); they may be produced by means of stimulation or variation of the excitability of the peripheral and central parts of the nervous system. Since biological objects are electrically heterogeneous and microwave-range electromagnetic fields (EMF) have a known selective thermal effect on various tissues and organs, a difference between a microwave effect and a neutral heat effect is not necessarily due to an unknown extrathermal factor, but might well be a function of an uneven distribution of heat in the organism which could exert its own peculiar effect.

It is important to realize that temperature input signals arise in many body structures among which the following have been identified experimentally: the preoptic-anterior-hypothalamus; posterior hypothalamus; mid-

brain, medulla, motor cortex, and thalamus; spinal cord; skin and respiratory tract; and viscera. All of these except the motor cortex and thalamus have been shown to evoke behavioral and/or physiological responses to changes in local temperature. These two areas have been identified as locations of cells having firing rates with high temperature coefficients but which do not seem capable of evoking thermoregulatory activity by local temperature changes alone (99). Stress is known to cause the secretion of a corticotropin-releasing factor (CRF) which stimulates the pituitary to release adrenocorticotrophic hormone (ACTH) which in turn causes the adrenal gland to release corticosterone, a hormone carried back to the pituitary to shut off the release of further ACTH. Both active and passive types of avoidance behavior are potentiated by ACTH and reduced by corticosterone.

McAfee (97, 98) points out how data can be misinterpreted to be the result of some unknown effect of microwave absorption, when hyperthermal effects (increased core temperature) are not involved. In cats, when peripheral nerves are stimulated by 45°C temperature, adrenal medullary secretion occurs and a rise in blood pressure is developed as a result of adrenalin secretion (49). It is well known that the halogenated hydrocarbon anesthetics in combination with injected adrenalin frequently produce ventricular arrhythmias (100). With some anesthetic agents the heart rate increases in dogs, and in unanesthetized animals heart rate is modified by an analeptic response if the latter is accidentally produced (97). McAfee (98) questions whether experiments on the effect of microwave radiation on heart rate are carefully controlled for this possibility. If so, it is not mentioned in the literature.

The intensity of electrical membrane potential of animal muscle and nerve cells is generally in the range of -70 to -110mV; animal cells cultured *in vitro* may show values as low as -10 to -30 mV, and protozoan cells have been shown to display potentials in the range of -30 to -100 mV (101). Due to their selective permeability, electrical double layers are formed at biological membranes which cause differences of potential between both sides of the membrane. Therefore,

the membranes are placed within electrical fields which are conditioned by electrical double layers. The gradient of these fields is considerable. It amounts to 10^6 V/cm with a potential difference of 100 mV and a membrane thickness of 100 Å. For microwave energy to be effective, therefore, tremendous fields have to be exerted to cause any effects (102). Microwave fields are only capable of applying a potential to a biological membrane which is many orders of magnitude smaller than the resting potential and, for this reason, should be unable to excite or change normal patterns (6, 8, 9). There is a great deal known about the excitation of membranes by both direct and low frequency alternating currents. In these cases, excitation is possible with current densities of the order of 1 mA/cm² in tissue. At higher frequencies and particularly at microwave frequencies, much higher current densities are required to cause excitation if it is at all possible. It is difficult to perceive, therefore, how microwave fields can affect excitable biological membranes at power densities less than those which would cause thermal effects (9).

On the basis of presentations by Illinger and Schwan (103), the following should be noted. Fundamental to predictions concerning the dielectric behavior of membrane is the accuracy of the model employed. The currently accepted Hodgkin-Huxley model is consistent with the concept that for excitation of membranes by external electromagnetic fields two conditions are required: (a) the field strength must exceed the membrane firing potential, and (b) the period of the field must equal or exceed the refractory period of the membrane. If any inadequacies exist in the Hodgkin-Huxley model, these criteria might not apply; in particular, other models for the nature of extracellular fluids may predict effects on membrane excitation through intermolecular rearrangement. The fact that dielectric saturation of biopolymers requires very large field strengths of the order of 10 kV/cm suggests the vanishing likelihood of protein denaturation by electromagnetic fields at low field strengths. The accumulation of energy in a membrane via external fields is inconsistent with the Hodgkin-Huxley model. It should be pointed out, nevertheless, that there exists the possibility

that effects at the biological system level may not be predictable on the basis of the behavior of isolated molecular systems.

Occupational Surveys and Case Reports

A number of retrospective studies have been done on human populations exposed to microwave energy. These have been, for the most part, either radar operators and repairmen or personnel involved in production and testing of tubes and microwave equipment, primarily radar. The studies may be divided into essentially two categories: those seeking general effects, and those specifically seeking changes in the lens of the eye. Analysis of these reports in the context of clinical and epidemiological approaches is warranted.

Daily (104) conducted the first studies on United States Navy personnel who were exposed over a period of time in the operation and testing of relatively low powered radar. No evidence of radar-induced pathology was found. Lidman and Cohn (105) examined the blood of 124 men who had been exposed to microwaves for periods from 2 to 36 mo. They concluded there was no evidence of stimulation or depression of erythropoiesis or leukocytopoiesis. A decade later, Barron, Love, and Baraff (106, 107) reported on a large group of radar workers who, along with a control group, were put under a 4-yr surveillance program. During this period, they underwent repeated physical, laboratory, and eye examinations. The examinations failed to detect any significant changes in the subjects. The incidence of death and chronic disease, sick leave, and subjective complaints was comparable in both groups. Some eye pathology was identified, but none with causal relation to the hyperthermia produced by microwave absorption. Fertility studies revealed essentially the same findings for both groups. Laboratory studies and chest X-rays were noncontributory. In the earlier report (106), these authors noted "paradoxical" blood changes, i.e., an apparent decrease in polymorphonuclear cells and increase in eosinophils and monocytes. In the later report (107), however, the authors note this was due to a variation in interpretation by a laboratory technician.

Cataracts

Most epidemiological studies in the U.S. have involved the ocular lens. The few available reports (39-43) contain findings that are questioned by competent ophthalmologists (108). Zaret (42, 43) has stated that from all the reports of others and his own studies, he accepts five reported cases of microwave cataracts as having occurred prior to 1968. In 1968 he presented 26 new ones, of which only one had progressed to a clinical cataract with loss of vision. By 1969, he had found a total of 42 cases of microwave cataracts of which he classified 11 as advanced and 31 as incipient.

As noted by Milroy and Michaelson (28), as of 1971, there were 44 reported cases of microwave cataract, if one accepts the 42 cases of Zaret (42, 43) and rejects other cases as not relevant due to inadequate reporting. Even if we were to accept the previously reported cases and Zaret's (42, 43) 11 "advanced" cases as being clinically significant and possibly related to microwave exposure, we have a total of 16 cases in the entire world.

In commenting on his surveys, Zaret (43) stated: "All except one of the cases had repeated exposure to power levels in excess of 100 mW/cm². For the solitary individual who is an exception to this rule, it can only be stated that he worked in a laboratory environment where research and development of microwave generating equipment were constantly being performed, that also, he was unaware of any microwave hazard and that there was a high probability of his having had multiple covert exposures to intense levels of microwave irradiation . . . Regarding microwave irradiation practically all of the individuals with positive findings were selected for examination because of known exposure to high levels of irradiation."

A paper by LaRoche et al. (109) of a study by Zaret exemplifies the problem in trying to establish valid cause-effect relationships. This paper reports "ophthalmic microwave injury" in 33 employees at an Air Force base. The authors state ". . . however, since preemployment examinations do not normally include examination specifically for microwave injury, there is either limited or no information available con-

cerning the prior condition of the lens." Also, of these 33 individuals, only four were negative at the initial examination. One, therefore, has no means of relating the results of the examination to previous history. Most important, the authors state ". . . it is not certain if those persons showing evidence of microwave injury on first examination actually received the exposure while working on the Air Force base."

While some of the epidemiological surveys may indicate a statistically significant increase in lenticular defects in microwave workers, none has shown any clinically significant defects in terms of decreased visual acuity. The scoring methods used for both degree of exposure and lenticular defects in all cases were not particularly sound, and their validity has been questioned (27). Lenticular opacities have also been noted to appear at the positions of existing microscopic congenital changes and, on reaching a certain magnitude, progress no further even when there is no change in the occupational setting (110). Such studies are only qualitative and do not give any relation between the actual power level and pathology. It should also be recognized that individuals studied in such surveys could have been exposed to ionizing radiation just as well as to microwaves.

The few adequate case reports of humans exposed to microwaves by means of diathermy treatment in the area of the eye are also extremely revealing, since, in these reports, multiple exposures at power densities of 80-240 mW/cm² did not result in cataract production even at a considerable time after exposure (111-114). The only reports of cataract production in man which do give some indication of possible field intensity or power density measurements are those of Hirsch (115) and Zaret et al. (116); in each of these cases, however, chronic exposure was experienced at levels well above 1 W/cm².

If one carefully reviews the human data that are available, information derived from human case reports and studies actually adds little to our knowledge of microwave cataractogenesis. The human data alone do not even provide conclusive evidence that microwave exposure causes cataracts in man. None of the case reports of cataracts can be conclusively at-

tributed to microwave exposure although in some cases there may possibly be an association. Retrospective studies of microwave workers have provided only a finding of clinically insignificant opacities, possibly representing an aging effect (117). Densitometry generally has not been very good, if available at all. In most cases, rough estimates of intensity are given in terms of "exposure scores." No data are available on the frequencies to which workers have been exposed, and, in most cases, exposures have been in a wide range of frequencies. The levels, however, with which clinically significant cataracts have been tenuously associated, have generally been quite high and point to a threshold well over 100 mW/cm². Little else can be concluded from the available human data. Many of the personnel exposed to microwave may also have exposure to X-rays emitted from high voltage tubes used in microwave generators. The extent and significance of these exposures is not well known. As ionizing radiation can also produce posterior subcapsular cataracts, it is possible that this could be a quite significant etiological factor in cataracts among microwave workers (28). Similar types of posterior subcapsular cataracts have also developed in man after therapeutic administration of corticosteroids (118) as well as other drugs or exposure to various chemical agents (119).

In a study by Appleton and McCrossen (120), 226 individuals occupationally associated with microwaves to varying degrees, some of whom had been included in the series reported by Zaret (43), were subjected to ophthalmological examination and compared to a population not associated to as great an extent with microwaves. The authors note that the equipment to which these people were exposed included sources that were rather powerful microwave emitters, and the potential for personnel exposure could have been at the highest level encountered. Some of the workers examined were involved in this type of work for 25 years. These authors conclude that available clinical evidence does not support the assumption that cataracts which develop in personnel performing duties in the vicinity of microwave generating equipment are a result of microwave exposure unless a specific instance of severe exposure can

be documented and correlated with subsequent cataract development.

Odland (121) has noted that on the basis of retrospective epidemiological study of cataract incidence in the USAF, the incidence of cataract had remained stable over the 10-yr period studied; minor variations were well within statistical limits of random variation. The results did not indicate significant trends in incidence of cataracts within age groupings, except the rise with age consistent with the natural history of this abnormality. This survey was based on a review of incidence data on Air Force personnel, worldwide during the period 1959-1968. It included individuals that had served in the Armed Forces during the period 1943-1954, were involved with the use of rf energies in military operations, and many remained in their 20 year career field of radar maintenance repair and operation. Odland (121) points out that "we could certainly expect an increase in cataract incidence if the almost unrestricted exposure limits of 1943-1957 did, in fact, cause cataracts. Based on incidence rates, the 10 mW/cm² exposure limit is certainly safe since previous unrestricted exposures caused no increase in incidence of ocular defects." Joly and Servantie (122) also reported that there was no evidence of radar induced cataract in the French Air Force over an 8-yr observation period.

Reproduction

Reports of sterility or infertility in the human from exposure to microwaves are questionable. Barron and associates (106, 107) found no evidence of fertility changes in their human surveys. There is one case report of altered fertility in a man from unusually large exposures to microwaves from radar (123). The difficulty in evaluating this report is that there was no pre-exposure examination of this individual, so any causal relationship is very tenuous. The authors note that "the patient was a repairman at a weather radar installation where he had been employed for four years. He frequently performed maintenance on the radar antenna while the equipment was in operation. He did not wear protective clothing. On occasion, while working

near the microwave beam, the patient noted a sensation of warmth . . . (the) patient was exposed repeatedly to microwave power densities more than 3000 times the currently accepted safe level established by the U.S. Air Force . . . and, furthermore, wore no protective garments . . . The ordinary precautions currently in use near microwave transmitters appear adequate to preclude excessive exposures such as this patient experienced."

There is very little information on the response of the human female. Rubin and Erdman (124) observed that neither conception nor pregnancy in humans was disturbed by therapeutic microwave diathermy application. Disturbance in menstruation is mentioned by Osipov (125) as one of the effects of an electromagnetic field on the individual, although the results of other studies of women working 3-11 yr in microwave fields do not support this report (126).

Effects reported by Marha and associates (127, 128) include: decreased spermatogenesis, altered sex ratio of births, changes in menstrual patterns, retarded fetal development, congenital effects in newborn babies, and decreased lactation in nursing mothers. They also report an increased incidence of miscarriages in women working with microwaves. Because of these reports, adolescents and gravid females are not permitted to work with HF, VHF, or UHF equipment as a preventative measure (128). According to these authors, such effects occur at thermal microwave exposure intensities (greater than 10 mW/cm²). It must be noted that in some countries a far larger number of women are employed in the industrial work force than in others, and many of these women work "swing shifts" after taking care of their families during the day. The influence of such interacting variables may have been overlooked in these surveys. One would like to see more details relating work cycle/work shift information of the affected women, and how it affects the menstrual patterns of women and the lactating abilities of nursing mothers who are part of an occupationally equivalent control population, especially with respect to work shift. These reports raise the question of what effect does working a regular job, or irregular shifts have on lactation

and menstruation in general. Also, what is the incidence and prevalence of miscarriages in the general working population that is equivalent to the microwave-exposed group in every way except exposure.

Genetic Effects

Sigler et al. (129) reported that there was a higher incidence of children with Down's syndrome among parents with prior occupational exposure to radar. In contrast to the mothers, the fathers of defective children did not have significantly greater exposure to ionizing radiation than did the control fathers. No differences were found in the occupations of the fathers of defective children and the controls, except for a higher frequency of military service for the fathers of genetically defective children—63.1% as compared with 56.6% for control fathers. In addition, a history of radar exposure was obtained from fathers, which indicated that 8.7% of the fathers of the children with mongolism and 3.3% of the control fathers had had contact with radar, both in and outside of the armed forces—a difference which is of borderline statistical significance ($p < 0.02$) (130).

It should be noted that the authors themselves only suggested the relationship between Down's syndrome and paternal radar exposure. The radiation history of the fathers provided a contrast to that of the mothers. There was a marked similarity in the history of radiation exposure reported by the fathers of genetically defectives and of the controls, except for the suggested relationship between Down's syndrome and paternal radar exposure. With this finding is a chance observation. It is exceedingly difficult to relate any increased incidence to possible exposure history of the parent unless large numbers of well-documented cases can be correlated with precisely known exposures; this was not the case in this study.

Neural Effects

A number of effects in man referable to CNS sensitivity has been described primarily by

Soviet and other East European investigators (40, 72, 76, 79, 80, 125, 128, 131, 133). The greatest emphasis is placed on effects produced at less than "thermogenic" power flux densities ($<10\text{mW/cm}^2$). According to these investigators, the basic symptomatology and neuropathology underlying all of the reported syndromes is described as due to the functional disturbance created in the CNS by nonthermal mechanisms. These effects are reported to occur in occupational exposures at levels far below those required to produce a temperature rise. The symptoms are manifested by weakness, fatigue, vague feelings of discomfort, headache, drowsiness, palpitations, faintness, memory loss, and confusion. These syndromes are apparently completely reversible in most cases, with little or no time lost from work (125). Much of these reports is based on subjective rather than objective findings (134). It should be noted that individuals suffering from a variety of chronic diseases may exhibit the same dysfunctions of the central nervous and cardiovascular systems as those reported as a result of exposure to microwaves.

Dodge (135), in his review of the Soviet research in this area, has stated "An often disappointing facet of the Soviet and East European literature on the subject of clinical manifestations of microwave exposure is the lack of pertinent data presented on the circumstances of irradiation. . . important environmental factors (heat, humidity, light, etc.) are often omitted from clinical and hygienic reports." A point that should be noted is that in the West the effects reported by East European investigators have not been observed, even at much higher exposure levels.

Frey (136, 137) has reported that individuals can detect pulse-modulated electromagnetic energy at wavelengths of 10–70 cm and at average power densities of 0.4 to 2.1 mW/cm^2 . The reported sensations were usually of an auditory nature and described as hissing, buzzing, or clicking sounds. These reports have been considered to be indicative of a direct neural effect of microwaves. There is no evidence, however, that this auditory sensation constitutes a risk of injury. Considering that many sources of auditory sensation exist in the nor-

mal environment and are not considered hazards, more evidence of hazard is required. This phenomenon is apparently not due to direct stimulation of neural fibers but rather to stimulation of the cochlea through electromechanical field forces by air or bone conduction (138, 139).

It is quite apparent that we cannot make very final conclusions regarding the biological effects of microwaves in man based on the information currently available. There should be well planned, clinically oriented occupational surveys. Additionally, careful review of reported effects should be conducted by competent persons to determine their validity. Extensive but sound, reliable, objective experimental and clinical investigation should be undertaken to determine the presence of these reported effects, the levels of exposure at which they occur, and the extent to which they may represent a hazard to the individual.

Standards

During the last quarter century there has been a marked development and increased utilization of equipment and devices for military, industrial, consumer use, and medical applications that emit a large variety of non-ionizing radiant energies; these include ultraviolet, infrared, visible light, microwaves, and radiofrequency. Of these the pathophysiologic consequences of exposure to radiofrequency or microwave energy has created the greatest interest, concern, and misunderstanding.

Microwaves of certain wavelength, intensity, and duration of exposure can produce biological effects which may be beneficial as well as harmful. For the general population and those persons exposed or with potential for exposure to this energy, personnel exposure guidelines and product emission standards have been promulgated. Personnel protection guides or exposure standards are usually those established by the American National Standards Institute (ANSI), American Conference of Governmental Industrial Hygienists (ACGIH), or Department of Defense. Legislation for personnel exposure and product emission levels are covered under

the Occupational Safety and Health Act of 1970 and the Radiation Control for Health and Safety Act of 1968, respectively. It is important that distinction be carefully made between product emission standards and personnel exposure standards and how they relate to potential injury. A proper perspective and realistic assessment of the biomedical effects of these radiant energies is essential so that the individual or general public will not be unduly exposed nor will research, development, and beneficial utilization of these energies be hampered or restricted.

Ideally, effect or threshold values should be predicated on firm human data. If such data are not available, however, extrapolation from well-designed, adequately performed, and properly analyzed animal investigations is required. In discussing standards for microwaves, it is necessary to keep in mind the essential differences between a "personnel exposure" standard and a "performance" standard for a piece of equipment and how they relate to each other. An exposure standard refers to the safe (incorporating a safety factor of at least 10) level of whole-body exposure and exposure time. This standard is a guide to people on how to limit exposure for safety. An emission standard (or performance standard) refers not to people but to equipment and specifies the maximum emission close to a device which ensures that likely human exposure will be at levels far below this limit which essentially is several orders of magnitude below the personnel exposure standard. As an example, one can cite the standards for microwaves. For personnel exposure the standard is 10 mW/cm². For microwave ovens the emission or product performance standard is 1 mW/cm² at manufacture and a maximum of 5 mW/cm² throughout the lifetime of the oven. This level is measured at 5 cm from the external surface and should be considered in relation to a restricted field with only a small area of the body potentially exposed.

Conceptually, as well as practically, these guidelines bear no relationship to the use of these energies in the context of medical diagnosis and treatment and should not be applied for such purposes. These standards for product emission and personnel exposure are

designed to protect the general public and the worker, and are based on entirely different criteria than one would apply for diagnostic and therapeutic purposes. In the medical context, on the basis of occupational and general personnel protection standards, individuals are grossly overexposed to radiant energies to achieve a specific diagnostic or therapeutic result. Diathermy at 2450 MHz creates incident energy exposures on a watt level to achieve desired tissue heating. To draw a parallel with ionizing radiation, used therapeutically, the localized exposures of cancer patients to incident ⁶⁰Co - radiation grossly exceed current guidelines for general population and occupational exposures.

Microwave exposure standards for most of the Western world are based, with minor variations, on those developed in the U.S. (Table 1). The original U.S. standard was tentatively adopted about 15 yr ago on the basis of theoretical considerations by Schwan and his associates. This standard was based on the amount of exogenous heat which the body could tolerate and dissipate without any resulting rise in body temperature. This tolerance level was calculated to be 10 mW/cm² for continuous exposure. Intensive investigation into the biological effects of microwaves was subsequently carried out by the U.S. Department of Defense. None of these investigations was able to produce any evidence for a biological effect at levels even approaching the theoretical level of 10mW/cm², and, indeed, no conclusive evidence was established for any effect below the level of 100 mW/cm² (15).

The ANSI standard of 10 mW/cm² for radiofrequency exposure recommended in 1966 and reaffirmed in 1973 (140) is roughly a factor of ten below thresholds of damage by thermal effects, assuming a long duration of exposure—i.e., 15 min or more. The 10 mW/cm² level is based on thermal equilibrium conditions for whole-body exposure. For normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 GHz, the radiation protection guide is 10 mW/cm² and the equivalent free-space electric and magnetic field strengths: approximately 200 V/m root-mean-square (RMS) and 0.5 A/m RMS, respectively. For modulated fields, power

Table 1. Recommended maximum permissible intensities for radiofrequency radiation.

Maximum permissible intensity	Frequency, MHz	Country or Source	Specifications
10 mW/cm ²	10–100,000	U.S.A.S.I., 1966; Canada, 1966	1 mWh/cm ² for each 6 min
	30–30,000	Great Britain, 1960	Daily exposure
	1000–3000	Schwan and Li, 1956	Whole body
		U.S. Army and Air Force, 1965	10 mW/cm ² continuous exposure 10–100 mW/cm ² , lim. occup.
		All	Sweden 1961
	German Fed. Republic, 1962	—	
1 mW/cm ²	700–30,000	U.S. Electronics and Communicat. Ind., 1956	Whole Body
	All	Sweden 1961	General Public; prolonged occupational exposure
	>300	USSR, 1965; Poland, 1961	15–20 min/day
0.5 mW/cm ²	All	Nato, 1956	
0.1 mW/cm ²	>300	USSR 1965; Poland, 1961	2–3 hr/day
0.025 mW/cm ²	>300	Czechoslovakia, 1965	CW, 8 hr/day
0.01 mW/cm ²	>300	USSR, 1965	6 hr/day
		Poland, 1961 Czechoslovakia, 1965	Entire day Pulsed 8 hr/day
20 V/m	0.1–30	USSR 1965	
10 V/m	0.01–300	Czechoslovakia, 1965	Pulsed 8 hr/day
5 V/m	30–300	USSR, 1965	

density and the squares of the field intensities are averaged over any 0.1-hr period, i.e., none of the following levels should be exceeded in any 0.1 hr period: electric field strength squared, 40000 V²/m²; power density, 10 mW/cm²; energy density, 1 mWh/cm². This guide applies whether the radiation is CW or intermittent and applies to the general public as well as workers.

There is no evidence in the scientific or medical literature of the Western world, that

the present U.S. standards represent a hazardous exposure level. The ANSI standard has been accepted by OSHA and with very little modification throughout the Western world. Microwave exposure standards for most of the Eastern European nations are based, with minor variations, on limits established by the USSR (Table 1). These limits, promulgated in 1959 by the USSR Ministry of Health are: 0.01 mW/cm² for an entire workday; 0.1 mW/cm² for

2 hr; 1.0 mW/cm² up to 20 min. These standards are based on vague "asthenia" syndromes reported by individuals who work with microwave/rf energies. These effects have not been demonstrated by Western investigators.

The apparent discrepancy in maximum allowable exposures between Eastern European and Western countries may be due to differences in industrial hygiene philosophy. Magnuson et al. (141) have noted that in the USSR, maximum permissible exposure (MPE) is based on presence or absence of biological effects without regard to the feasibility of reaching such levels in practice. The Soviet MPE represents a desirable level for which to strive rather than an absolute value to be used in practice.

The apparent differences in U.S. and Eastern European standards are based not on actual factual information but on differences in basic philosophy. These differences appear in the areas of industrial hygiene, basic scientific research, and reporting of scientific data. Another area in which large differences exist is that of technology such as instrumentation.

The basic radiometric instruments in the USSR are the PO-1 power flux density meter, a wide range and reasonably accurate instrument consisting of several cabinets and weighing 80 kg, and the P2-2, which functions as an indicator for electromagnetic fields exceeding the allowable limit (132). The U.S., on the other hand, has several portable survey meters of reasonable accuracy and range for screening microwave ovens and industrial operations as well as radars. In addition, more sophisticated equipment is available for scientific investigations and application.

Problems and Perspectives

Although there is considerable agreement among scientists concerning the biologic effects and potential hazards of microwaves, there are areas of disagreement. It is essential that research be fostered and advanced to counteract the often-voiced "what we don't know can hurt us" attitude with consequent overly restrictive and unrealistic standards. In spite of the fact that the quantum energy in the microwave por-

tion of the electromagnetic spectrum is too small to cause rupture of even the weakest chemical bonds in any biological structure, several theories of a molecular mechanism of microwave action have been suggested. None of these hypotheses has yet been proven.

There also is a serious philosophical question about the definition of hazard. One objective definition of injury is an irreversible change in biological function as observed at the organ or system level. With this definition it is possible to define a hazard as a probability of injury on a statistical basis. It is important to differentiate between the hazard levels at which injury may be sustained and effect or perception. All effects are not necessarily hazards. In fact, some effects may have beneficial applications under appropriately controlled conditions. Microwave-induced changes must be understood sufficiently so that their clinical significance can be determined, their hazard potential assessed, and the appropriate benefit/risk analyses applied. It is important to determine whether an observed effect is irreparable or merely transient or reversible, disappearing when the electromagnetic field is removed or after some interval of time. Of course, even some reversible effects may be unacceptable under some circumstances.

A critical review of studies into the biological effects of microwaves indicates that many of the investigations suffer from inadequacies of either technical facilities and energy measurement skills or insufficient control of the biological specimens and the criteria for biological change. A large body of dependable data on the biologic effects of microwave exposure has been accumulated, nevertheless, without any incontrovertible evidence of subtle, longterm or cumulative effects.

A factor that has been a source of continuing concern is the problem of measurement of energy absorbed by biological tissue. Knowledge of the incident energy is inadequate to explain what is happening within biological structures, and these occurrences must be correlated with absorbed energy. In some cases of microwave exposure we are incapable of describing the incident energy, not to speak of its absorption, as is the case in the near-field of a microwave source.

The phenomena of reflection, transmission, and energy absorption occur in biological tissues that are exposed to microwaves. These phenomena occur not only at the initial entry point or exposed area, but also at deeper tissue interfaces such as the fat-fascia-muscle layers, and within tissues themselves. Frequency specificity of interactions may create complex problems. Considerable effort will have to be expended in this area before problems, controversies, and existing confusion can be resolved.

More sophisticated conceptual approaches and more rigorous experimental design must be developed. Proper investigation of the biologic effects of microwaves requires an understanding and appreciation of biophysical principles and comparative biomedicine. Such studies require interspecies "scaling," the selection of biomedical parameters which consider basic physiological functions and work capacity, identification of specific and nonspecific reactions, and differentiation of adaptational or compensatory changes from pathological manifestations.

For microwave bioeffects study, body size of the experimental animal must be taken into account along with accurate *in vivo* densitometric measurements so that results of an investigator obtained with one animal species can be related to those from another investigator using other species. Since body absorption cross sections and internal heating patterns can differ widely, an investigator may think he is observing a low-level or a nonthermal effect in one animal because the incident power is low, while in actuality the animal may be exposed to as much absorbed power in a specific region of the body as another larger animal is with much higher incident powers. In the performance of experimental studies on animals, it must be remembered that the changes depend to a major degree on the geometric dimensions, owing to the depth of penetration of microwave energy. Therefore, interspecies scaling is of utmost importance. Since the cardiovascular system plays a major role in thermal regulation in mammals, blood flow in a particular organ has to be considered.

Although most investigators accept the fact that high power density of microwaves can

result in pathophysiologic manifestations of a thermal nature, some reports have suggested that "low power density" microwave energy can affect neural function in animals and man. Most of these reports have emanated from the USSR and other Eastern European countries. Since most reported "low-level" effects relate to behavioral and CNS changes, studies are needed to determine the nature and mechanism(s) of the nervous system's reactions, if any, to electromagnetic and magnetic fields and to investigate the degree to which the individual's performance capabilities may be affected. Because of the important integrative and regulatory functions, the neuroendocrine and central nervous system (CNS) should receive attention as possible sensitive areas. The question whether reported CNS changes in man, if they are validated, would be important enough to affect his performance at the low permissible exposure levels, which do not endanger his immediate health and comfort, should be resolved (142).

It is not always possible to use generally accepted electrophysiological methods in studying the influence of microwave fields on the organism, since the sensors (electrodes, thermocouples, etc.) can act as receiving antennas so that substantial high-frequency voltages are induced in them during irradiation. These voltages may give rise to secondary but sometimes very strong stimuli ranging up to thermal coagulation of protein tissues. Unfortunately, investigators have at times overlooked this fact (143).

In the performance of experimental studies on animals, it must be remembered that the changes in the organism depend to a major degree on the geometric dimensions of the animals, owing to the depth of penetration of microwave energy which varies with wavelength. It is known that at a given wavelength (for example, $\lambda = 10$ cm), vitally important organs in mice and rats may absorb the electromagnetic energy, while in dogs and especially man, almost all of this energy is absorbed by the superficial tissues of the head, thorax, and abdominal wall. The brain, heart, etc., may escape direct irradiation in these cases (143). The concept of scaling, therefore, has to be invoked in all cases where extrapolation from

animal experiments to man is undertaken.

Specifically, the problem of measurement of power density is an overriding one. There is no question that interpretation of biological research is dependent on good energy absorption measurement. In addition to accurate measurement of the ambient electromagnetic fields, the amount of energy actually deposited in the tissue under investigation should be determined. Therefore, there is a need for an accurate general purpose reader, the development of implantable probes should be encouraged, and an integrating dosimeter would be of considerable utility in hazards assessment. In this context, one should not lose sight of the fact that, although good dosimetry and implantable probes are essential, these would be of no value unless there is a precise definition of the biological problem under consideration. Good laboratories with proper microwave sources, exposure and dosimetry facilities, and animal facilities are required.

Particular attention should be paid to instrumentation problems - to the development of more adequate probes for making measurements in the presence of electromagnetic fields. Field strength, electrophysiological, and thermal probes which will give artifact-free readings, will not distort the field in any way, and which will not give rise to inadvertent stimulation of the tissue due to induced currents are absolutely essential before any degree of reliance can be placed upon findings of altered physiology or behavior due to electromagnetic fields. Development of a personal dosimeter should have a very high priority.

A rational and intelligent appreciation is required between true radiation hazards which demand control of power sources and people exposed to high power densities therefrom and on the other hand, hazards involving interference to medical or other electronics resulting from radiation levels much lower than those biologically effective. Because our modern society permits a growing number of radiation sources, it is incumbent on designers and users of medical and other electronic devices to insure their compatibility with the modern electromagnetic environment. It should be appreciated that susceptibility of devices to low

levels of radiation is just as much a causative factor of hazard as is the inadvertent or uncontrolled radiation at power densities approaching biologically effective levels. It is becoming apparent that susceptibility standards need to be developed for electronic cardiac pacemakers and other electronic medical devices.

In any assessment of the hazards of exposure to microwaves, it is extremely important that a team approach be used consisting of physical and biological scientists working together. Physical scientists include individuals well grounded in electromagnetic field theory and electronics. Biological scientists include individuals with experience in such disciplines as genetics, behavioral sciences, physiology, biochemistry, and pathology, as well as individuals with broad or "horizontal" training such as one obtains in human or veterinary medicine. The physical scientists and biological scientists should be complemented by biophysicists who provide a bridge between these two major orientations.

Above all, there is a need for scientific competence and integrity. It is important to maintain a proper perspective and assess realistically the biomedical effects of microwave exposure, so that the worker or general public will not be unduly exposed nor will research, development, and beneficial utilization of these energies be hampered or restricted.

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