REVIEW ARTICLE

PHYSIOLOGICAL HAZARDS OF MICROWAVE RADIATION: A SURVEY OF PUBLISHED LITERATURE*

H. KALANT, M.D., Ph.D.,† Toronto

Powerful microwave generators, of the type used in present-day radar and television transmitters, and the much more powerful generators envisioned in the near future, generate several types of radiation which offer potential hazards to the life or health of personnel concerned with their operation. These radiations include not only the microwaves themselves, but also x-rays and small amounts of ultraviolet radiation. The biological hazards offered by the latter types of radiation are well known and well appreciated. Protection against these dangerous radiations is essentially a matter of good engineering in the design, construction and location of the units. The nature and extent of the possible hazard offered by microwaves themselves have been much less clearly established. Because of the increasing use of microwaves, and the steadily greater powers employed, it is essential to establish whether or not a health hazard exists, and what the nature and magnitude of any such hazard may be. The following remarks are concerned with this problem, and represent the conclusion reached on the basis of a survey of experimental and clinical observations published to date.

Present Extent of Hazard

The development of more recent high-output microwave apparatus has been accompanied by a highly commendable display of caution on the part of the authorities concerned. This has resulted in the relatively unusual situation in which a great deal of research has been devoted to the study of possible hazards before any proven mishaps have occurred. Two case reports have appeared in the medical literature, describing lesions occurring in patients exposed to radar waves. One report describes a case of bilateral cataract in a man working with a small microwave generator similar to those used for diathermy purposes. The lesions described are quite unlike those produced by microwaves in all the experimental studies, and the authors are careful not to claim that the lesions were caused by microwaves, but merely to urge caution. The second case is that of a man dying of diffuse peritonitis and appendicale abscess, following a one-minute exposure at unstated distance to the beam of a naval radar unit of unknown power. The lesions are in no way character-

istic of microwave exposure, and it seems virtually certain that an exposure of sufficient intensity to cause such lesions would have killed the patient rapidly through hyperpyrexia. Neither of the two cases reports gives sufficient information to permit even a guess concerning the actual intensity of exposure, and it seems improbable in the extreme that the lesions described were in fact caused by microwaves.

On the contrary, careful long-range medical observations on large groups of personnel working with radar have revealed no evidence whatever of acute or chronic damage resulting from their occupational exposure to radar waves.1, 2, 12

The numerous experiments with animals undertaken so far, however, show clearly that damage due to tissue heating by microwaves can most certainly occur. The level of microwave power required to produce such injuries, as will be discussed below, is seldom if ever encountered in normal operational use of present-day radar equipment, but the large increases in the power of radar apparatus which are contemplated in the very near future make it probable that serious health hazards to radar personnel will indeed arise. Therefore, the present concern with physiological injury produced by microwaves is a precautionary one, designed to anticipate and avoid future danger, through an understanding of the means by which injury is produced, and a satisfactory definition of the safe limits of exposure of personnel to microwaves.

Physical Characteristics of Microwaves and their Transmission

It is beyond the scope of this review to undertake any detailed consideration of the physics of microwaves. The following remarks are intended only to summarize those features of microwaves which are relevant to a discussion of physiological hazard.

Microwaves are electromagnetic radiations, intermediate in wavelength and frequency between the longer portion of the infra-red and the short or high frequency radio-waves. The exact differentiation between so-called UHF, or ultra high frequency radio-waves, and microwaves is a matter of definition and usage. According to current usage, microwaves are those ranging from 1 mm. to 30 cm. in wave length.13 Various wave bands used in radar, in long-distance telephony and in television signal relay are included in the microwave group. However, the bands of interest with respect to physiological hazards are those lying between 100 cm. and 1 cm. wave length. Since all electromagnetic waves have a velocity of $3 \times 10^{10}$ cm. per second, these wave lengths correspond to frequencies of 300 to 30,000 megacycles per second (Mc/sec.) respectively. While the 300 Mc waves are not microwaves according to present electronic usage, in the present paper they will be considered

*From the Physiology and Biochemistry Wing, Defence Research Medical Laboratories, Toronto.
†Present address: Department of Pharmacology, University of Toronto.
together with microwaves, with respect to physiological hazards.

The average power, the duty cycle, and the spatial distribution of energy may vary greatly, depending upon the individual characteristics of the microwave generator. For example, existing units range from 100 to 1000 watts output, but by engineering modifications quite within the range of present knowledge, it is anticipated that 20 to 30 kilowatt outputs are quite feasible, while future developments may make possible powers greatly exceeding even these values. The duty cycle may also be varied between very wide limits. For example, for radar use it is desirable to operate the generator in very short bursts of high intensity, allowing sufficient time between bursts for the impulses to reach their target and be reflected to the observing post without causing interference with the following impulses. The duty cycle refers to the interval between the commencement of one burst of power and the commencement of the next burst. Thus, a 0.1% duty cycle would mean that a very short burst of power would be followed by a silent interval 99.9 times as long, followed by a second short burst of power and another long silent interval, and so on. Most radar sets operate on such short duty cycles. Using the illustration given above, a peak power output of 5 megawatts during each burst of power would correspond to an average power output of only 5 kilowatts through the full cycle. For television transmission purposes, the time or duty cycle is usually 100%. Under these circumstances the peak power output and the average power output are identical.

From the generator the microwave output is usually conducted along a wave guide, which is a hollow metal channel, of rectangular cross-sectional shape and dimensions such that reflection and distortion of the wave pattern are minimized. The wave guide terminates in a funnel or horn which delivers the radiation to an antenna from which the microwaves are dispersed into the atmosphere. In television broadcasting, it is usually desired to distribute the radiation widely over a very large target area, so that an essentially non-focusing type of antenna with little or no gain in power density* is used. For most applications of microwaves, such as radar and communication relay, it is usually desirable to focus the radiation emitted from the funnel of the wave guide into a compact beam, for more effective transmission to a selected target over a long distance. Since the optical behaviour of microwaves, particularly those of very short wave length, resembles that of visible light, a reflecting antenna of parabolic or other suitable shape is used in such units for the purpose of focusing the microwaves into a narrow beam, with consequent gains of 600 to 1000-fold in power density. This ability to be concentrated into an intense beam is one of the factors giving rise to the special hazards of microwaves. The beams, however, are always somewhat divergent rather than completely parallel, so that the power density tends to decrease as the square of the distance from the virtual focal point, in a manner analogous to the behaviour of focused light.

When microwave radiation reaches a target, it may be reflected from the surface, penetrate and be absorbed by the target, pass completely through the target and beyond, or show some combination of all of these forms of behaviour. The proportions of the incident energy which are reflected, absorbed, or transmitted unchanged, will depend upon many factors including the wave length of the microwaves, the texture and spatial orientation of the target surface, the composition of the target, and its thickness. When the target is a human being or experimental animal, the problem is considerably complicated by the inhomogeneity of the target. Thus, the presence or absence of fur, hair or clothing, the thickness and texture of the skin, the thickness and water content of the subcutaneous fat, the thickness and orientation of the various planes of deep fascia, all have a marked influence upon the absorption and conversion of microwave energy within the body. Schwann and his collaborators have calculated on theoretical grounds the curves of energy absorption at various depths below the skin surface, for microwave radiation of different wave lengths, in subjects with much or little subcutaneous fat, when the incident energy is assumed to be delivered at right angles to the skin surface. They have demonstrated mathematically that under these conditions the proportion of energy absorbed is approximately 40% for frequencies below 1000 Mc/sec. or above 3000 Mc/sec. In the frequency range of 1000 to 3000 Mc/sec., the percentage of absorbed energy varies from 20 to 100%, depending upon the factors mentioned previously.

The depth distribution of the absorbed energy within the body also varies greatly. Radiation of a frequency greater than 3000 Mc/sec. behaves essentially like infra-red radiation, being practically all absorbed within the thickness of the skin itself. With frequencies below 500 Mc/sec., the radiation penetrates deeply and absorption occurs diffusely within the body. At frequencies between these two values, the distribution varies markedly from one individual to another depending upon the factors of tissue structure mentioned above.

In summary, it may be stated that the great number of variables involved in microwave generation, focusing, air transmission, and absorption characteristics of the target, make it impossible to predict from the initial power output of the apparatus what the final result will be in terms of energy absorbed by the exposed subject. Each case must be assessed individually, and it is apparent that the range of variation is enormous.

*Power density is used throughout this report to mean the rate of delivery of energy to a unit area normal to the direction of propagation. “Flux” is an adequate alternative term.
MECHANISMS OF MICROWAVE ENERGY CONVERSION IN THE TISSUES

Probably because of the wide interest in ionizing radiation, and because of the fact that the continuous spectrum of electromagnetic radiations includes x-rays and gamma rays, there has been a certain measure of confusion in some quarters with respect to the results of absorption of microwaves. It should be pointed out that chemical activation, in the sense of ionization or free radical formation, such as that induced by ultraviolet rays, x-rays, or gamma rays, does not occur as a result of microwave irradiation. Although it is still convenient for many purposes to talk of the electromagnetic radiations in terms of waves and wave lengths, their photochemical effects can only be grasped in terms of modern physics, according to which these radiations are described as consisting of individual quanta, or discrete bundles of energy, travelling at the speed of light. The energy value per quantum is characteristic of each type of radiation, and is inversely related to the wave length, e.g. one quantum of ultraviolet radiation of 2536 Å wave length has 400,000 times as much energy as one quantum of 10 cm. microwave radiation. A given molecule will only absorb those radiations of which one quantum corresponds exactly to the energy requirement for some change in state which the molecule can undergo. A crude but useful analogy might be to compare quanta of different types of radiation to coins of different values, and a complex molecule to a vending machine. If a vending machine be imagined, which dispenses only cigarettes in response to a twenty-five cent piece, and only matches for a one cent piece, then the deposit of 25 one cent coins will produce only 25 packages of matches, and not cigarettes. In this analogy, we may substitute the effects of various changes of energy state in the molecule for the various products dispensed, and ionization can be compared to the cigarettes, one quantum of x-rays to a twenty-five cent piece, and one quantum of microwaves to one cent. In other words, the energy value of one quantum of microwaves is much too low to produce the type of excitation necessary for ionization, no matter how many quanta are absorbed. Chemical activations involving orbital transitions of electrons are rarely encountered with radiation of wave length longer than that of ultraviolet, or possibly visible light (photosynthesis). Even the much smaller transitions in energy level associated with alteration of inter-atomic bonds within a molecule (those giving rise to the so-called vibrational and rotational spectra) are too large to be produced by quanta of microwaves. These changes are characteristically associated with infra-red radiation.

The only transitions between energy levels that can be effected by microwaves are the extremely small transitions associated with changes in magnetic orientation of an atom or molecule. Ordinarily, within the permanent magnetic field provided by the earth, the energy requirements for these orientational transitions are so low that they are met by very long wave electromagnetic radiation. If a strong external magnetic field is applied, however, the energy requirement for these small transitions is increased. This fact is used to advantage in the study of the internal magnetic fields of various molecules. By applying an extremely strong external magnetic field, the energy requirement for these small orientational transitions is made to coincide with the quantal energy values of microwaves. This forms the basis for the procedure known as paramagnetic resonance analysis. It should be noted that this is not an effect of microwave irradiation, except under the artificial condition resulting from a simultaneous application of an extremely strong magnetic field.

Certain interesting magnetic orientation effects of microwaves can be demonstrated with biological materials in vitro. One of these effects is known as pearl chain formation. When suspensions of oil globules in water, or of erythrocytes or lymphocytes in saline, are exposed to very low power microwaves, the globules or cells line up in chains resembling strings of pearls, oriented along the lines of force of the magnetic field. The chains are readily broken up by mechanical agitation, by increased Brownian movement resulting from heat, or by switching off the microwave field. A second orientational phenomenon of possible interest is that known as dielectric saturation. This is observed when solutions of proteins or other macromolecular substances are exposed to microwave fields of moderately strong intensity. All of the ionizable side chains of such molecules also tend to become oriented along the lines of the magnetic field, tending to break hydrogen bonding or other secondary inter- or intra-molecular linkages, and altering the zone of hydration on which the solubility of the molecules depends. This may lead to non-thermal denaturation or precipitation of the molecule.

By far the most important effect of microwave absorption, however, is the conversion of the absorbed energy into heat. All the radiant energy absorbed is ultimately transformed into increased kinetic energy of the absorbing molecules, which, by increased collision with adjacent molecules, produce a general heating of the entire medium. However, this dissipation of heat throughout the whole mass of the target requires a finite time, and it is clear that within the tissues of an irradiated subject there may exist considerable local differences in temperature during the time of exposure. These differences depend chiefly upon the differences in water content of the various tissues, and upon the presence or absence of interfaces capable of reflecting the microwave radiation. Thus, heat generation is greatest in those tissues with a high content of water, and is also enhanced locally in the areas adjacent to bone or tough fascial planes.
which act as reflecting surfaces. This will be considered further in relation to the problem of tissue damage.

**Experimental Lesions Produced by Microwaves**

The fact that microwaves of appropriate frequencies can generate heat deep within the tissues has been known for over a decade and forms the basis for the clinical use of microwave diathermy treatments. It also underlies the development of rapid cooking apparatus using microwave generators. It is evident that the rise of temperature in an irradiated body or tissue will depend upon the amount of energy absorbed and converted to heat, minus the amount of heat dissipated by conduction, radiation, or other means. In the case of a single organ or tissue subjected to localized microwave radiation, the dissipation of heat is dependent chiefly upon the magnitude of blood flow through the part, the circulating blood serving as a cooling system. Thus, temperature rise resulting from moderate irradiation of the normal human arm or leg is self-limited, in that the temperature rise which reaches a maximum in 10 to 20 minutes is then reversed by a marked local increase in blood flow. In relatively ischaemic tissues, such as the eye or the testis, dissipation of heat is effected essentially by conduction to the surface. This is a relatively inefficient mechanism, and continued irradiation can result in sustained local temperature rises of as much as 10 to 20°C.

The production of characteristic lesions in irradiated organs is found to parallel the production of such temperature rises. In the eye, the characteristic lesion is a small, irregular or punctate subcapsular opacity, at the posterior pole of the lens, appearing after a latent period of two to 14 days following exposure to microwaves. Unless the exposure has been so severe as to cause an intense acute inflammatory reaction in the eye, the opacities usually begin to regress after a while, and within a few weeks disappear completely or leave small punctate scars. It has been shown that adenosine triphosphatase and pyrophosphatase in homogenates of lens tissue are very easily destroyed by temperatures of the order of those found in microwave-irradiated eyes. However, no loss of activity of these enzymes was found in eyes with small localized posterior cataracts, so that the mechanism of cataract formation must be dependent upon some other damage not as yet known.

The characteristic lesion found in the testis is a degeneration of the epithelium lining the seminiferous tubules, and a sharp reduction in the numbers of maturing spermatocytes in the lumen. There is a patchy irregular distribution of damage within the testis, adjacent tubules often showing markedly different degrees of degeneration. The damage is indistinguishable in character from that produced by the external application of heat to the testis, and is almost certainly fully reversible, as is the latter except in severe cases.

When the whole body is subjected to microwave irradiation, the radiation absorbed is converted to heat, and must be dissipated by the various means at the disposal of the body, including radiation, conduction, and evaporation of sweat. When these protective measures are insufficient to dissipate the heat as rapidly as it is developed, the circulation of the blood serves to spread the heat from the irradiated portions diffusely throughout the body, resulting in a rise in general body temperature. The magnitude of this rise will of course depend upon the degree of imbalance between heat production and heat loss. If the rise of temperature is excessive, the damage produced is indistinguishable from that due to fever of any origin. During the rise in temperature, reactions indicative of a nonspecific pituitary-adrenal response to stress occur, including a sharp decrease in eosinophils and lymphocytes, and a rise in leucocytes. Severe hyperpyrexia carried to the point of death results in diffuse degenerative lesions throughout the body, including renal tubular degeneration, myocardial degeneration and necrosis, haemorrhagic lesions in the gut, respiratory tract and liver, and diffuse haemorrhagic and degenerative lesions in the Purkinje cells, cerebral cortical neurons, and other brain structures. Fatally exposed animals develop acidosis, hyperpnoea, lacrimation and tetany, and finally die of respiratory arrest.

A variety of other effects of localized or whole body microwave irradiation have been investigated by American and European workers. Very intense microwave fields of up to 10 watts per sq. cm. applied directly to the head have been shown to cause deterioration of conditioned reflex activity in dogs. This is hardly a surprising finding, and adds little to our knowledge since no measurement of cerebral temperature change was made, and no pathological studies of brain damage are quoted. Whole body irradiation with a 130 watt radar apparatus producing 15 cm. radiation was found to have no effect upon blood pressure and circulation time or myocardial function. Whole body irradiation of near-lethal intensity was reported to cause a decrease in blood glutathione, while in vitro irradiation of serum caused no specific alteration in serum lipase or amylase activity. These studies are virtually useless for the purposes of the present survey, since they give no details of power density, body temperature of the animals, or other indices of the severity of exposure. Another group of workers has studied the effects of 3 cm. and 10 cm. microwaves upon body growth, plasma volume, and tissue plasma content in exposed mice. The findings are taken to suggest highly specific non-thermal effects of various wave lengths upon these parameters of mouse growth. However, no statistical assessment of the significance of the
findings is presented, and the controls do not include animals exposed to environmental heat at levels which they can tolerate without rise in body temperature. The results therefore add little to the understanding of the mechanism of microwave effect.

**BIOLOGICAL SIGNIFICANCE OF NON- THERMAL EFFECTS OF MICROWAVES**

As mentioned previously, certain magnetic orientation effects of microwaves can be demonstrated *in vitro*. Pearl chain formation can be shown with erythrocytes and lymphocytes, but it seems extremely doubtful that this phenomenon can have much biological significance in large animals, including man. Mechanical agitation such as the circulation of blood, and thermal agitation resulting from strong microwave irradiation, tend to break up the chains. Therefore, the phenomenon is usually observed with microwave fields much too low to cause any recognizable biological damage. The phenomenon of dielectric saturation, mentioned above, may possibly apply to proteins within living tissue, because this process can be observed with field strengths known to cause lesions in experimental animals. To date, however, there is only one piece of evidence which may suggest such an effect in living animals as a contributory factor in the production of lesions. This evidence consists of the finding that pulsed radar waves with a high peak power are more effective in producing cataracts in the rabbit's eye than continuous output of the same average power. Thus, a single 20 minute exposure to 12 cm. pulsed radar waves on a 50% duty cycle, with a peak power of 0.28 watt per sq. cm. (equivalent to continuous power of 0.14 watt per sq. cm.) produced opacities in 8 out of 12 rabbits, while a 20 minute exposure to continuous power of 0.14 watt per square cm. did not produce opacities. The thermal effect is a function of the average power only. This finding, therefore, raises the possibility that non-thermal denaturation of protein in the lens, which may well be related to the peak power, might be an auxiliary factor in the production of lesions in at least some tissues.

It has been claimed that direct irradiation by microwaves is capable of producing non-thermal damage in developing teleostean ova, as shown by a higher percentage of developmental anomalies in ova exposed to radar than in control ova heated to the same temperature as that measured in the irradiated medium. Similar claims have been made for non-thermal sterilization of bacterial cultures by radar fields (see 7 for references). However, extremely careful and thorough experiments with cultures of *E. coli* and other bacteria, exposed to various radar fields of up to 600 megacycles in frequency and 100 kilowatts peak power, led to the conclusion that the only bactericidal effect is thermal.

The latter authors point out the great difficulties in accurate temperature measurement by non-experts.

A recent report describes certain morphological changes in the nuclei and chromosomes of cells in garlic root-tips growing in water, when exposed for five minutes to 27 Mc/sec. radiation of unstated power, operating on a duty cycle of .004 to .009. These effects are again described as non-thermal, though no description is given of the method of measuring the temperature. This is a particularly important omission in the work cited, since the electrodes were separated by a distance of only a few millimetres, much of which was occupied by glass insulation. The volume of water must have been very small indeed, and the cooling relatively rapid on termination of radiation exposure. Under such conditions, accurate measurement of temperature change within the root-tips must be an extremely difficult technical problem. In the absence of definite information, it would be well to reserve judgment on the question of whether or not the observed changes are truly non-thermal.

Another interesting report of non-thermal effects of microwaves, unfortunately not well documented, concerns the production of temporary motor paralysis in small animals on exposure to low-power microwaves. The immediate disappearance of paralysis on termination of radiation suggested that the symptoms may have resulted from interference with the electrical phenomena of nerve impulse conduction by resonance with the microwave field. Such resonance, if true, would be critically dependent upon the wave length of the microwaves, and the dimensions of the nerve structures of the animal.

In summary, though non-thermal effects may conceivably contribute to the development of lesions in subjects exposed to microwave irradiation, by far the most important factor is the production of heat through microwave absorption with consequent effects of either local tissue damage by heat, or hyperpyrexia in the whole organism.

**QUANTITATIVE ASPECTS OF MICROWAVE HAZARD**

One of the most pressing concerns of both military and civilian authorities with respect to biological effects of microwaves is the establishment of safe limits of exposure of personnel in the course of duty. It has been pointed out in the preceding sections, however, that the only meaningful criterion of exposure is the quantity of energy absorbed, and not the energy produced by the apparatus. It is extremely difficult to make a precise assessment of energy absorption under conditions normally encountered in radar operation. Certain experimental approaches provide a reasonably accurate measure of energy absorption. In one approach, the subject is exposed to microwaves within a wave guide or other closed space in which the pattern of cross-sectional energy distribu-
tion is known. From the area of profile of the subject, it is possible to make a reasonable calculation of the total energy absorbed. Such an arrangement bears almost no resemblance to the conditions of exposure under actual operation of radar installations. A second approach, which bears more resemblance to practical conditions, consists of irradiating the test object under free space conditions (e.g., in a room lined with completely absorbent material), and measuring the scatter of radiation in all directions from the test object. From such measurements, together with a measurement of the temperature increase in the test object, it is possible to compute the fraction of energy absorbed in the specimen. Both these methods fail to allow for the effects of air movement, humidity, and temperature, which influence greatly the heat loss by live subjects, especially man. However, they do permit an attempt to establish thresholds of exposure for the production of tissue lesions.

By such means, it has been established that a power density of 0.1 watt per sq. cm. applied directly to the eye can be tolerated for hours at a time with no production of cataract. There is some disagreement concerning the lowest effective intensity. Carpenter states that a 10 minute exposure at 0.28 watt per sq. cm. will cause opacities, while Williams et al. state that a 90 minute exposure at 0.29 watt per sq. cm. is required to produce cataracts, and Ely et al. state that an indefinite exposure at a density of 0.2 watt per sq. cm. does not cause any damage. All are agreed that with higher field strengths, cataracts can be produced by much shorter exposures. Williams et al. demonstrated cataract formation with a single exposure of 5 minutes at 0.59 watt per sq. cm., 20 minutes at 0.40 watt per sq. cm., 40 minutes at 0.32 watt per sq. cm., and 90 minutes at 0.29 watt per sq. cm.

An important practical question is that concerning the possibility of cumulative damage resulting from repeated sub-threshold exposures. Conflicting opinions have been expressed concerning this problem, but the bulk of evidence does not support the concept of cumulative damage from sub-threshold exposures. All workers who have investigated simultaneously the intraocular temperature changes and the occurrence of lenticular damage on acute microwave irradiation, agree that there is a critical intraocular temperature which must be reached before opacities develop. This temperature, as reported by various authors, ranges from 45 to 55°C. On termination of exposure, the temperature of the irradiated eye returns gradually to normal, and obviously no cumulative rise of temperature can occur if the intervals between exposures exceed the cooling time to normal temperature in the tissue or part concerned. The only 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, however slight. The problem may be somewhat confused by two factors. The first factor is the difficulty of accurate measurement of field strengths, as discussed in a previous section of this review. This may account for the rather large variations in threshold values for cataract production by single exposures, mentioned in the preceding paragraph. The second factor is the lag period of 2 to 14 or more days between the time of effective exposure and the appearance of lenticular opacity. This delay must correspond to a period of initial metabolic disturbance in the eye, directly caused by the microwave exposure, which gives rise to the subsequent morphological change. Since even the morphological changes are capable of regressing, it would be reasonable to expect that the functional damage, if not too severe, might regress without going on to form a visible lesion. The meaningful threshold value, then, should be that exposure which causes the initial biochemical lesion, rather than the obvious delayed morphological result. To date, however, it has not been possible to identify the basic biochemical lesion and so establish such a threshold value. This may be the reason why a few repeated exposures, each of which is very slightly below the single-exposure threshold for cataract production, can give rise to opacities [(8), and p. 243 of (37)], while a great many daily exposures to definitely sub-threshold power can be tolerated with no sign whatever of ocular damage [p. 193 of (37)].

Despite the disagreements mentioned above, there is on the whole fairly good agreement concerning the power densities and exposure times required to produce cataracts in animals as different in size as the rabbit and the dog. It is much more difficult, however, to define a maximum safe exposure limit with respect to the production of hyperthermia resulting from whole body irradiation. This greater variability is due to many factors. For example, the thickness and texture of the animal's fur and skin, the ratio of surface area to body mass, and the body size in relation to the wave length of radiation employed, all affect the efficiency of absorption of microwave energy and its conversion to heat. On the other hand, the mechanisms of thermo-regulation available to each species, and their efficiencies, will affect the degree of damage resulting from production of a given amount of heat within the body. In this respect, man is perhaps the best protected of all animals. Rabbits, for example, can tolerate an indefinite exposure to a power density of 0.01 watt per sq. cm. with no rise in temperature, but show a 1°C rise with a flux of only 0.02 watt per sq. cm., and some deaths from hyperthermia occur in two hours at a power density of 0.03 watt per sq. cm., or in half an hour at 0.06 watt per sq. cm. In contrast, human beings exposed to a flux of 0.22 watt per sq. cm. for 48 minutes showed a slight fall in rectal temperature, due to
the efficiency of the sweating mechanism in the dissipation of heat.19

Of the various tissues and organs examined, the testis appears to be the most sensitive in terms of the minimum exposure which can produce any recognizable lesion however small. Ely et al.19 studying dogs, rabbits and rats, attempted to estimate a safe limit of exposure in terms of the lowest power value required to cause any testicular damage in the most sensitive animal of the group. On this basis, an exposure of 0.01 watt per sq. cm. was considered the threshold for testicular damage, on an indefinite exposure. However, the authors point out that the damage observed with such low levels of exposure is extremely slight, almost certainly fully recoverable, and in no way differentiable from that due to such commonplace factors as, for example, a hot bath. They question, therefore, whether such damage should be legitimately considered a basis for appraisal of hazard from microwaves.

From the accumulated experimental observations, it becomes clear that each species differs from the rest in terms of relative sensitivity of different organs and tissues to microwave damage. It is therefore inaccurate to extrapolate to man on the basis of experimental observations on rats or rabbits. Moreover, as explained previously, these estimates of threshold values for production of lesions are based on experimental situations which in many cases do not resemble actual operational situations involving exposure to radar. Thus, such factors as environmental air temperature, humidity or wind strength have obvious significance with respect to the efficiency of thermo-regulatory mechanisms. For this reason, they have important effects upon the power absorption necessary to produce hyperthermia. Studies on cataract formation, in addition, have been mainly carried out by exposure of the eye directly to a microwave source at a distance of approximately one inch. Quite small variations in the distance of the eye from the source produce marked differences in the number and severity of lesions caused.28 From a practical point of view, exposed individuals are hardly likely to be at exactly the same distance from a radar source on each exposure, and there is little value to a set of safety regulations which would have to stipulate separately for each radar generator the maximum safe exposure time at each of a series of distances varying by a few inches or feet. In addition, the fact of whole body exposure, by altering the body temperature, also alters the amount of exposure to the eye or testis required to raise the local temperatures in these organs to a point of damage.

In view of these difficulties, the only feasible method of establishing a maximum safe exposure limit is one which almost certainly errs widely on the side of safety. This method consists of taking the lowest exposure known to cause any sort of damage in the most sensitive animal, and allowing an additional factor of safety consisting of one or two orders of magnitude. Since most workers cited above agree that an indefinite exposure of 0.1 watt per sq. cm. will not cause hyperpyrexia or ocular damage in man, this figure forms the basis for presently established safety limits. Interestingly enough, this figure was also reached by Schwan25,46 on theoretical grounds, as the maximum safe value for indefinite exposure, on the assumption that a heat load, sufficient to double the surface dissipation of energy derived from metabolism, could be safely borne by a normal subject. The additional safety factor applied varies on the basis of personal preference rather than fact.27 The United States Air Force employs a factor of 10, setting a maximum safe exposure at 0.01 watt per sq. cm. Others29 recommend a safety factor of 100, suggesting a maximal direct exposure of 0.001 watt per sq. cm., on the basis that reflected energy must be taken into account, and that there is in fact no need for exposure during proper operation of radar apparatus.

Bearing in mind the actual circumstances associated with the use of radar or other microwave apparatus, it seems fairly clear that these maximum exposure limits are seldom if ever reached. Operating personnel have virtually no reason to be within the focal point of a radar antenna. Beyond the focal point the intensity falls off so rapidly that even with a 20 kilowatt transmitter, the power density 30 to 40 feet away is only 1/1000 of noonday solar radiation at the equator.49

A recent calculation48 suggests that a 20 kilowatt transmitter distributing 35 cm. microwaves from a parabolic antenna of 10 m. diameter, mounted 10 m. above the ground and directed horizontally, would have a danger zone covering all the ground between 300 yards and half a mile in front of the antenna. However, this is based on an assumed maximum safe exposure of 0.01 watt per sq. cm., with an additional safety factor of 4. In the light of the experimental studies with human beings cited above, this assumed maximum appears to be considerably lower than necessary. There is therefore no real contradiction between these two statements,48,49 the difference being merely in the magnitude of the arbitrary safety factor used. Moreover, for most uses of radar, the transmitter is not fixed but constantly rotating, so that an exposed subject is only momentarily irradiated and then has the rest of the scanning cycle in which to dissipate absorbed energy before the beam again reaches him. Finally, most radar installations are aimed upwards rather than horizontally, for obvious reasons, so that operating personnel and others on the ground are likely to be exposed only to the very weak radiation at the margins of the beam, or scattered from distant reflecting surfaces.
FUTURE RESEARCH AND DEVELOPMENTS

The reassuring facts in the previous paragraph may not be valid for many more years. With future technical developments in radar, it is probable that extremely powerful transmitters with average outputs of up to 600 kilowatts will be employed in certain areas. Strategic considerations may require that the antennae of these units be fixed in position, rather than in constant movement. This would mean that marginal scatter and reflection from fixed surfaces might well assume dangerous proportions. The nature of the danger, however, would not in any way differ from that which has been discussed in this survey. The problem would then be a practical one of at least two components. One component problem would be the development of a dose rate meter simulating tissues of a living organism, so as to measure not the power produced by the apparatus, but the probable power absorbed and converted to heat under any given set of circumstances. The Richardson dosimeter is a start in this direction, but it has not yet been perfected. The second component problem would be the use of such a meter in mapping out the danger areas surrounding the radar installations. The solution of the problem would be essentially an engineering one, consisting of the provision of adequate shields and safeguards to keep operating personnel out of the recognized danger areas. Certain emergency maintenance duties may occasionally require personnel to work within known danger areas. For such purposes, a small, rugged, and easily read power density meter must be available for use within the danger areas, and suitable protective garments must be devised.

Basic research into the mechanisms of interaction of microwave energy and biological tissues is required, both for the most efficient and beneficial use of microwave therapy, and for the recognition of minimal degrees of physiological damage. However, practical protection of human beings against damage due to excessive microwave energy appears to require chiefly the application of common sense and sound engineering directed against known dangers, rather than a search for new and as yet unrecognized dangers.

The author wishes to express his gratitude to Mr. J. E. Kennedy of D.R.M.L. and to Professor H. E. Welsh of the University of Toronto for valuable discussions during the preparation of the manuscript, and to Mr. G. Cowper of A.E.C.L. and Mr. J. W. Cox of D.R.B., Ottawa, for their most helpful criticisms and suggestions.

REFERENCES

17. DILLON, T. S. et al.: Heatimg characteristics of laboratory animals exposed to ten centimeter microwaves, N.M.I. Research Report, Project NM 001 568.12.02, 1957.