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BIOLOGICAL EFFECTS OF MICROWAVE RADIATION*

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(*Received* 1 *July* 1970; *in revised form* 1 *September* 1970)

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INTRODUCTION

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INTRODUCTION

ONLY OVER the past two decades has the potential hazard of microwave irradiation come to any significant degree of attention. This is not to say that its potential hazard had not been recognized. As early as 1926 Duke-Elder suggested that electromagnetic radiations at the "long wave lengths" might be cataractogenic.[1] He cites production of cataracts by Leyden jar discharge as early as 1888. With the coming of the Second World War and increasing use of microwaves in radar, some concern was expressed as to the hazard to the radar operators and repair men. Indications at the time seemed to indicate that there was no hazard to humans.[2,3] In the post-war and Korean Conflict period, however, evidence began to accumulate pointing toward a definite hazard existing, based on exposure of animals to rather intense irradiation.[4–8] During the 1950 s, greater interest was shown in the microwave hazard problem culminating in 1957 with the establishment of the Tri-Service Ad Hoc Committee by the Air Force in 1957 to study the potential hazards associated with exposure to microwave fields and to establish safe exposure levels.[9] A maximum safe exposure level of 0.01 W/cm^2 was established on the basis of this committee's recommendation.[10]

Over the past few years, the problem of potential hazards from microwave radiation has come sufficiently to the fore to be considered in legislation by the Congress of the United States.[11,12] With the increasing use of microwave ovens for cooking, both commercially and in the home; with the use of microwave diathermy as a therapeutic tool; and with the ever-increasing power output in radar systems, even into the megawatt range, it is obvious that standards must be set to control the use of microwave devices and to safeguard the public from potential hazards in their use. It is appropriate at this time to review the presently available information concerning the biological effects of microwave radiation and to point out deficiencies in our knowledge, clarification of which is necessary before any sound and reasonable standards can be set for microwave exposure.

CHARACTERISTICS OF MICROWAVE RADIATION

Microwave radiation falls in the band of wavelengths from roughly 30–300,000 MHz, overlapping at the ends with the radio and infra-red portions of the spectrum. This corresponds to wavelengths from the millimeter through the meter ranges. Photon energies in these ranges are approximately 10^{-5} eV per photon.[13] The significant portion of this range, as a physiologic hazard, is the 1 cm to 100 cm range, frequencies between 300 MHz and 30,000 MHz.[14]

Power outputs of microwave generators range

* This paper is based on work performed under contract with the U.S. Atomic Energy Commission at the University of Rochester Atomic Energy Project and has been assigned Report No. UR-49-1314.

from less than 100 W (measured at the waveguide) for diathermy apparatus to millions of watts for high power radar sets.[15] Exposures are generally measured in terms of the power flux, i.e. watts per square centimeter (W/cm^2). This parameter varies with the type of antenna (focusing or non-focusing), with the inverse square of the distance from the focal point and with reflections or perturbations of the field caused by objects in the field. The duty cycle of the generator, i.e. the percentage of time the power is actually on, is also an important parameter and varies from 0.1 % for radar to 100 % for an oven or diathermy apparatus.[14]

ENERGY ABSORPTION IN TISSUE

When a microwave beam impinges on a target any one or a combination of three things may occur. It may be reflected; it may be absorbed; or it may pass completely through the target. The actual effect depends on the wave length of the radiation and the orientation, composition, and thickness of the target. When the target is a biological organism the presence of fur or hair and clothing, as well as the relative distribution of skin, fat and facia are significant variables in determining the amount of energy absorbed. In general, for the frequency ranges below 1000 MHz or above 3000 MHz approximately 40 % of the incident energy is absorbed by tissue. In the 1000–3000 MHz range absorption varies from 20 % to 100 % depending on the above factors. The depth distribution of energy is primarily in the skin for frequencies greater than 3000 MHz and is diffuse for frequencies less than 500 MHz. Depth distribution is variable for frequencies between 500 MHz and 3000 MHz. Microwave energy absorption in tissue has been analyzed both theoretically and experimentally by SCHWAN and PIERSOL.[16,17] Because of the many variables operating, microwave energy absorption can in no way be assessed on the basis of power output of the microwave generator.[14]

The energy of a microwave quantum is insufficient to produce ionization or excitation, being only about 1/400,000 that of an ultraviolet photon or about 10^{-5} eV. The only possible effects are a uniform volume heating due to movements of ions in the field or changes in the magnetic orientation of molecules which may be observed as pearl chain formation, as manifest by the lining up of red and white blood cells or bacteria along magnetic lines of force, or as dielectric saturation, in which protein side chains orientate along lines of force. The primary effect, however, is that of heating the tissue which, depending on relative water concentration and the presence of interfaces, may produce temperature differentials between tissues.[18,19]

THERMAL VERSUS NON-THERMAL EFFECTS

A great deal of controversy has arisen concerning the relative importance of thermal and non-thermal effects of microwave radiation. Thermal effects have been well demonstrated and documented but the evidence for a non-thermal effect is at best only suggestive.

Even the earliest work demonstrated considerable temperature rise in the eye on exposure to microwaves.[2] The work of Carpenter has demonstrated cataract production with temperature increases small enough to suggest a non-thermal effect.[20] IMIG *et al.* have found a temperature rise in the testes resulting in tubular degeneration similar to that found secondary to heating of the testes by other means.[5] Death due to hyperthermia with resultant degenerative lesions has been shown by BOYSEN.[21] MICHAELSON *et al.* have also well demonstrated the hyperpyrexic effect of microwave exposure and the pathological effects produced; in addition, they have shown thermal burns of the skin of dogs used in their work.[9,22]

Non-thermal effects of electromagnetic radiations of the "long wave lengths" on the lens of the eye were suggested as early as 1926 by Duke Elder. He postulated a mechanism consisting of an increased lability of colloids leading to derangement in metabolism resulting in protein coagulation.[1] If non-thermal effects are present, they must be due either to pearl chain formation or dielectric saturation. Pearl chains are easily broken by gentle agitation and it has been shown that they are of no biological significance as a microwave effect.[23] Dielectric saturation, however, can break hydrogen bonds and secondary links and may alter hydration of proteins leading to a non-thermal denaturation and precipitation of the protein.[14] Non-thermal biological effects might be possible by this mechanism.

Considerable experimental evidence has been put forth as supporting the conclusion that there is, indeed, a non-thermal effect of microwaves. Much of this evidence has been since criticized as not really demonstrating an absence of thermal effect. Dosimetry and thermometry frequently are quite questionable. The remainder of the evidence, which may be considered as experimentally sound data, is, at best, only suggestive of non-thermal effects on the basis that temperature rises noted have been held by the authors to be insufficient to produce a thermal effect.

Evidence presented for a non-thermal effect has generally been in one of several areas, microscopic, biochemical, cataract production, and neurological. Pearl chain formation with blood cells and bacteria has generally been held to be insignificant biologically.[14,23] The bactericidal effect and chromosomal aberrations described by Heller and Teixiera-Pinto[24] are probably thermal in nature.[14] Several metabolic defects, especially in relation to the lens of the eye, have been described. Daily *et al.* have found a decrease in ATPase and pyrophosphatase in lenses in which cataracts have been produced.[25] Richardson *et al.* have noted that alloxan diabetes decreases the threshold for cataract production and suggest a metabolic effect.[26] A decrease in ascorbic acid and glutathione content in the lens has been described by Merola and Kinoshita, working with Carpenter's group.[20,27] The ascorbic acid decrease may be demonstrated before any visible evidence of cataract formation. The suggestion of a non-thermal effect in cataractogenesis comes from the work of Carpenter *et al.*[20,28] He bases this conclusion on the fact that repeated "subthreshold" exposures will produce cataracts with a smaller rise in intraocular temperature than a single larger exposure with a greater rise in temperature which does not produce a cataract. He concludes that there is no critical intraocular temperature for cataract production nor a very appreciable temperature rise necessary; therefore, the cataractogenic effect must be nonthermal.[20] The majority of work in neurological and neuroendocrine effects of microwaves has been by Russian and other East European investigators.[29,30] Much of this work is Pavlovian in nature and describes changes in conditioned reflexes in animals[29] or neurasthenic responses in microwave workers.[30] Michaelson *et al.* have also described neurological and endocrine effects in dogs but believe them to be thermal in nature.[9,22] Motor paralysis has been produced in small animals but disappears when the exposure is terminated. It has been suggested that this may be a resonant effect on the electrical conduction of nerve.[14]

SPECIFIC EXPERIMENTAL EFFECTS

Whole body effects produced by microwave irradiation are essentially those of heating. Hyperpyrexia is produced when the experimental animal's thermoregulatory capacity is exceeded. The physiological response of the animal consists of acidosis, hyperpnea and lacrimation progressing to tetany and finally death due to respiratory arrest. Pathological changes described in animals in which death has ensued are quite similar to those found due to fever.[19,14] These are primarily degenerative changes in the brain, kidneys, and heart.[21] In animals sacrificed prior to death after microwave exposure a generalized congestion of the organs has been noted.[9] Direct thermal burns of the skin have been produced in some cases.[9] The effects on animals irradiated at sublethal levels appear to be those typical of "stress syndrome" as a response to thermal hypothalmic–hypophysial stimulation. This is expressed as a decrease in eosinophils and lymphocytes along with a rise in granulocytes. These effects have been investigated and discussed by Michaelson.[22] Neurological and neuroendocrine effects may also occur by this mechanism. Among the effects in this category is an increase in thyroid gland activity as manifest by an increased I^{131} uptake.[9,30] Reversible changes in conditioned reflexes manifested as a diminution of positive conditioned reflexes and a decrease in discrimination have been described by Livshits.[29] Only two specific effects have been described at exposure levels in which thermal damage to the whole animal would not be significant. Imig *et al.* have demonstrated testicular degeneration as a result of microwave irradiation. Degeneration of tubules and coagulation similar to that found in burn necrosis were produced with a rise in testicular temperature from 29 to 35°C. Sertoli and interstitial cells remained intact. These effects are similar to those produced by infra-red, hot baths or experimental cryptorchidism.(5) The reason for this effect has been attributed to the relatively poor vascular supply to the testis which is, therefore, less able to dissipate the excess heat.

The second, and by far best studied, specific effect of microwave irradiation is the production of opacities in the lens of the eye. Moncrieff *et al.*, in 1932, failed to produce cataracts in dogs exposed to diathermy. Their animals were killed at the conclusion of their exposure, however, so that they would have missed any latent effect.(2) Since that time many different investigators have produced cataracts or opacities under many different types of experimental conditions, so much so, in fact, that results of different investigators are generally in no way comparable. Different types of animals have been exposed to many different wave lengths at different power levels generated by different equipment. They have been exposed within wave guides, in near and far field, and with their eyes coupled to wave guides. Perhaps the greatest discrepancy is in dosimetry. Due to a lack of standard dosimeters, each investigator has designed his own method of dosimetry. Results, therefore, are in no way comparable. In general, two types of cataracts may be produced. At high power densities anterior cortical opacification may be produced and is apparent immediately after the exposure. In many cases inflammation of the external structures of the eye is also produced. There seems to be no question that this type of cataract is a result of a thermal effect on the lens. The second type is more typical of microwave irradiation at lower power densities in the range of 100 mW/cm^2 and is similar to the "radiation cataracts" described by Cogan *et al.*(31) These consist of granular or vesicular lesions appearing at the posterior pole of the lens and may be quite small and clinically insignificant or large and affecting vision. These appear with a latent period of 2–14 days and in many cases are found to regress with time. They may also progress with continued microwave exposure or may go unchanged. The most commonly used frequencies have been those between 2000 and 3000 MHz. There seems to be a threshold for opacity production at a power density of about 100 mW/cm^2. The majority of work in experimental microwave cataracts production has been done by Daily *et al.*(6,7,25,32) Richardson *et al.*,(8,26) and Carpenter *et al.*(20,29) Williams *et al.*(33) and Cogan *et al.*(34) have also studied microwave cataractogenesis. Birenbaum *et al.* have compared microwave cataractogenesis at several different frequencies with results suggestive of a decreasing effect with decreasing frequency.(35) Buchanan *et al.* have reviewed the effects of microwaves on the eye.(36)

A number of retrospective studies have been done on human populations exposed to microwave radiation. These have been, for the most part, either radar operators and repairmen or personnel involved in production and testing of microwave equipment, primarily radar. The studies may be divided into essentially 2 categories, those seeking general effects, and those specifically seeking changes in the lens of the eye. In 1943 Daily studied 45 men with microwave exposure histories ranging from 2 months to 9 yr. Several of these men reported frontal headaches and a flushed heating sensation when standing within 3 ft of a generating antenna. This effect disappeared when the exposure was ended and in no cases were physical abnormalities or hematologic changes noted. The men had normal reproductive histories and no skin or hair changes were noted.(3) In 1958 Knauf noted that no adverse effects had been observed in Air Force personnel exposed to microwaves.(15) Barron and Baraff, in 1958, studied 335 microwave exposed workers and compared them with a control population. No differences were found in physical inventories of the two groups nor were any differences in deaths, disease, sick leave or subjective complaints found. No blood or urine changes and no increase in ocular pathology of the microwave exposed group were noted. Both groups were equally fertile as determined by reproductive history.(37) A number of effects on the human body have been described by Russian workers. These effects have been summarized by Turner in a report based on translation of a book by LETAVET and GORDON.[30] Most of these effects are subjective, consisting of fatigability, headache, sleepiness, irritability, loss of appetite and memory difficulties. Cardiovascular effects consist of lability of the pulse and blood pressure, heart enlargement and murmurs and ECG changes. Increased ^{131}I uptake by the thyroid, changes in serum proteins, decrease in olfactory sensation, falling hair and disruption of sexual potency have also been noted. Cataracts have been observed as well as psychic changes including unstable mood, hypochondriasis and anxiety. The nervous and cardiovascular disruptions are noted to be benign and do not lead to loss of work capacity. On the basis of these reports the Russians have set their maximum exposure level at 0.01 mW/cm^2; a factor of 1000 smaller than the U.S. limit of 10 mW/cm^2. Although some of these effects have been noted in U.S. experimental data, none (except cataracts) have been noted in U.S. human studies. This would lead one to surmise that either the Russian subjects have been exposed to higher levels of microwave irradiation than U.S. workers, or perhaps are more prone to the subjective, neurasthenic, hypochondriacal complaints than U.S. workers. PAZDEROVA,[38] in Czechoslovakia, has reviewed the Soviet bloc and Western literature in this field and has pointed out that the apparent discrepancies perhaps are not so great as would appear. She points out that the Soviet literature presents very little data and cannot be statistically analyzed; that the Soviet work is based a great deal on subjective rather than objective findings; and that dosimetry in both cases is rather poor and not comparable from worker to worker. She states that "In order to judge the significance of the occupational hazard of electromagnetic radiation more accurately, it will be necessary to correlate medical findings obtained from long-term observations of workers exposed to electromagnetic radiation with the extent of exposure."

Several studies of lenticular opacities in U.S. microwave workers have been done. ZARET and EISENBUD, at the Fourth Tri-Service Conference in 1961, reported no late lens defects peculiar to microwave exposure. They did note a statistically significant increase in posterior polar defects.[39] ZARET *et al.* reported a study of 475 exposed personnel and 359 controls in which a slight, but statistically significant, increase in lenticular defects were noted in the exposed group. These consisted of posterior polar defects, opacification, minute defects and relucency. It is noted that their exposure and "eye score" indices are not entirely valid measures.[40] In 1966, CLEARY and PASTERNACK reported a study of 736 microwave workers and 559 controls. They, too, reported a statistically significant increase in certain types of lens defects. They suggest that this may represent an aging effect and note that there is no relationship to loss of visual acuity or cataract production.[41] MAJEWSKA has studied 200 Polish microwave workers and 200 controls. He, too, notes a statistically significant increase in lenticular defects. Again an aging effect is suggested.[42]

While all of these reports have found a statistically significant increase in lenticular defects in microwave workers, none has reported any clinically significant defects in terms of decreased visual acuity. The scoring methods used both for degree of exposure and lenticular defects in all cases are not particularly sound and their validity may be questionable.

Several case reports have been made concerning possible microwave effects on humans. In 1957, MCLAUGHLIN reported "Tissue Destruction and Death from Microwave Radiation (Radar)."[43] This is the only case of death reported in association with microwave exposure, and it is doubtful whether the microwave exposure had a significant effect, if any, in causing the death. It was, in fact, a case of acute appendicitis in which evisceration of the wound occurred on the tenth post-operative day leading to profound shock and death. KNAUF and KALANT both note that no other deaths from microwave exposure have ever been recorded and that deaths due to appendicitis and shock are not uncommon.[14,15]

The remainder of the cases reported are of cataracts occurring in microwave workers. These are considered to be clinically significant cataracts to distinguish them from the lenticular opacities noted in the studies of larger groups noted above. In 1952 a letter to the editor of the *Journal of the American Medical Association* reported bilateral cataracts in a 20 yr old radar repairman. The Journal editors replied that radar does not penetrate the cornea so that the cataracts could not be caused by the radiation.[44] Since that time several more cases have been reported and certainly no one presently would question the possibility of microwaves inducing lenticular opacities in spite of the fact that in most of the cases reported the role of microwaves may be quite legitimately questioned.

In 1952 HIRSCH and PARKER[45] reported bilateral lenticular opacities in a 32 yr old man with rather extensive exposure at a microwave test bench to power densities probably in excess of 100 mW/cm^2. The cataracts, however, were of the nuclear type rather than the posterior subcapsular which are characteristic of radiation cataracts. He was also noted to have uveitis and choroiditis.[45] Hirsch recently reevaluated this case, at which time the subject had had the left lens removed. There is a chronic uveitis and chorioretinitis in that eye. The cataract in the right lens remains stable. His exposure has been recalculated at several hundreds of mW/cm^2 for lengthy and repeated periods of time. This is certainly the best documented case of microwave cataractogenesis. While it is possible that the subject's intercurrent ocular disease may be related causally rather than as an effect, this case is certainly suggestive of a cataractogenic effect of microwaves at very high exposure levels,[46] KURZ and EINAUGLER reported a 51 yr old man with rather incidental and questionable exposure to microwaves who developed bilateral posterior subcapsular cataracts.[47] There have also been several cases of lenticular opacities reported in the Soviet literature. ZARET, at the 1968 and 1969 Meetings of the Aerospace Medical Association, reported on several new cases of lenticular opacities elicited by his studies. He accepts 5 reported cases of microwave cataracts prior to 1968 and presents 26 new ones, of which only one had progressed to a clinical cataract with loss of vision.[48] By 1969 he had found 42 cases of microwave cataracts of which he classified 11 as advanced and 31 as incipient.[49] If we accept the 5 previously reported cases and Zaret's 11 "advanced" cases as being clinically significant and probably at least related to microwave exposure, we have a total of 16 cases. It would be interesting to compare this incidence in microwave workers with the naturally occurring incidence of cataracts in the general population.

DISCUSSION

There are many unresolved dilemmas in the field of biological effects of microwaves. Before experimental data can be applied to hazard evaluation and standard setting as pertains to occupational exposures, many discrepancies must be resolved. These discrepancies arise in terms of instrumentation, experimental animals, and frequency variation of microwaves. Also to be resolved are problems of thresholds, cumulative effects and residual injury.

That the frequency of microwave irradiation is a significant factor in determining biological effect is not questioned. It has been clearly shown that effects vary with the frequency used. The most significant effect in terms of cataract production seems to be in the 2000–3000 MHz range. For this reason, frequencies in this range probably represent a greater hazard. It is possible, of course, that this is only an apparent effect due to the fact that most of the work has been done in this range of frequencies. At lower frequencies, however, (e.g. the 300 MHz range) near-lethal exposures have not produced cataracts. At higher frequencies (e.g. 10,000 MHz) greater power densities are needed to produce cataracts.

Variation in the types of generators used in the power outputs as well as variations in the conditions of exposure of the animal, i.e. near field, far field or within the wave guide, presents problems in comparing effects observed in different studies. The lack of a standard dosimeter presents a very great problem in that each investigator has set up his own system for measuring exposure. These have consisted of measuring temperature increases, measuring power outputs and calorimetric determinations using phantoms. This particular area of difficulty may be resolved to some extent with the use of power density meters which are now becoming available.

A great deal of work in the field has been done using rabbits as the experimental animal. As man's thermoregulatory capacity far exceeds that of the rabbit, or most other possible experimental animals, one wonders what effect this would have on hazard evaluation. The fact that most of the rabbits used have been albinos leads one to question what differences might be expected with pigmentation. It is conceivable that pigmented skin is more resistant to microwaves than it is to ultraviolet. It is also possible that there are differences between pigmented and albino eyes. CARPENTER believes that pigmentation is not significant but DAILY *et al.* have reported a definite difference in cataractogenesis between pigmented and albino rabbits.[32]

The presence of a threshold exposure for cataractogenesis seems to have been well demonstrated for rabbits. This threshold appears to be about 100 mW/cm² although Carpenter has found an effect with repeated exposures at 80 mW/cm².[20] Whether this represents a cumulative subthreshold effect is essentially a question of semantics. As these effects are not noted when sufficient time elapses between exposures it would appear that this simply represents an accumulation of injuries which have not had sufficient time to be repaired. There is no evidence to indicate any true Residual Radiation Injury, defined as an irreparable fraction of radiation injury, such as produced by ionizing radiation.[22]

CONCLUSIONS

The question of microwave hazard evaluation presents a very considerable problem. There are many areas in which presently available data are questionable, contradictory, or inapplicable. Many of the deficiencies presently extant in microwave hazards investigations must be eliminated before good sound data will be available on which to base microwave exposure standards. The present U.S. standard of 10 mW/cm² has been in effect for about 15 yr. This value has been questioned many times and several suggestions have been made that it be lowered. The present Soviet maximum permissible exposure is 0.01 mW/cm², a factor of 1000 lower. It is questionable whether the Soviets can, in fact, function within this limit. This limit was reached, to a great extent, on the basis of psychological and neurasthenic response in exposed personnel which have not been observed in this country. It is highly questionable whether any of the presently available experimental data can be validly applied to humans and used as arguments favoring lowering of the present Maximum Permissible Exposure of 10 mW/cm². Only in the coming years, with the development of better equipment for generating, measuring and recording microwave energy, will this problem be solved.

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