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ABSTRACT

The ever-expanding use of microwaves and utilization of greater and greater intensities calls for a periodic evaluation of microwave hazards. The present evaluation is based upon experimental animal data and observations on radar personnel in the armed forces and industry. The injury caused by microwaves is mainly thermal. Non-thermal effects have not been proved beyond doubt. Experimental irradiation of animals is very different from the actual exposure of man in radar operation. Also man, in comparison with experimental animals, has a much more efficient thermo-regulatory mechanism. Extrapolation of animal data to man is, therefore, of limited value unless inter-species and intra-species variability is recognized and considered. Additional hazards such as those due to ionizing radiation and toxic agents have been considered. Proper engineering and lay-out of equipment, education of personnel and observance of certain precautions are practical and effective preventive measures which can be instituted without jeopardizing or interfering with radar operations. This should not lead to complacency and neglect of vigilance and search for possible ill-effects due to microwaves.

SINCE WORLD WAR II when the use of radar for military purposes became widespread it has become increasingly apparent that exposure to the microwave energy used in this equipment may be hazardous to operating personnel. The potential hazard becomes greater as energy levels of radar devices increase.

The term "microwaves" generally refers to electromagnetic radiation ranging in frequency from 100 to 3000 Mcycles. This corresponds to wave lengths of 3 M to 1 cm. In the electromagnetic spectrum "microwaves" occupy a position between the infrared radiation band which has higher frequencies and the radio broadcast band on the lower frequency or longer wavelength end.

It is known that electromagnetic energy in the microwave range produces heat in the body of the exposed individual. Reports of the non-thermal effects have also been made which are not fully substantiated. Cataracts have been produced in experimental animals and some have been observed in human workers.

The purpose of this paper is to evaluate the hazard due to microwaves based upon experimental work on various animals and observations made on the personnel involved in microwave technology and radar development.

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MODE OF ACTION OF MICROWAVES IN TISSUES

Microwaves, because of their comparatively low quantum energy, are a form of non-ionizing radiation. For example, one quantum of ultralviolet radiation of 2536 A° wave length has 400,000 times as much energy as one quantum of 10 cm. microwave radiation. By increasing the flux density of microwaves the number of quanta will increase but the energy level per quantum will remain unaltered. The type of change of state of a given molecule (ionization or otherwise) depends upon the basic quantum energy of the radiation rather than the number of those particular quanta.

Microwaves produce thermal and non-thermal effects on biological materials. The thermal effect is considered by many to be the more important of the two.

Thermal—When microwaves reach a target they 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 these forms of behavior. The proportion of the incident energy which is reflected, absorbed or transmitted unchanged will depend upon many factors including wavelength of the microwaves, the texture and spatial orientation of the target surface and the composition and thickness of the target. When the target is a human being or an animal the inhomogeneity of the target further complicates the problem. Thus the presence or absence of fur, hair or clothing, the thickness of skin and subcutaneous fat, the orientation of various planes of deep fascia, water content of the tissues, all have a marked influence upon absorption and conversion of microwave energy within the body.

It has been demonstrated mathematically and experimentally on phantoms that the proportion of microwave energy absorbed is approximately 40 per cent for frequencies below 1000 Mcycles/sec. or above 3000 Mcycles/sec. In the frequency range of 1000 to 3000 Mcycles/sec. the percentage of absorbed energy varies from 20 to 100 per cent depending on the factors mentioned above.[13, 14]

The depth distribution of the absorbed energy within the body also varies greatly. Radiation of a frequency greater than 3000 Mcycles/sec. behaves essentially like infrared radiation, being practically all absorbed within the thickness of the skin itself. With frequencies below 500 Mcycles/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 thickness mentioned above.

The absorbed energy is ultimately transformed into

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increased kinetic energy of the absorbing molecules, which by increased collision with adjacent molecules, produce a general heating of the entire medium.

Non-Thermal—The possibility that microwaves may interact with biological material without the production of a significant amount of heating has been pointed out by various workers.

Garlic root tips have exhibited mutations when grown in a high frequency field, microorganisms have swum in preferred directions associated with the field direction, snails and planaria have shown the ability to sense the presence and polarity of very weak electric and magnetic fields, several people have heard sounds which correspond to the frequency of modulation of an incident microwave beam, some fish are able to navigate by detecting distortions in their self-penetrated electric field, visual stimuli have resulted in humans from fields too weak to depolarize visual neurons in the usually understood way, and changes have been reported in the paper electrophoretic pattern of human gamma-globulin after isothermal irradiation by microwaves.[16]

There is thus no doubt that a biologically significant interaction with electromagnetic fields is possible for which tissue heating is not the cause. There is no presently understood physical basis that can explain these diverse non-thermal effects.

Four distinct mechanical effects have been observed in vitro: 1.) Pearl chain formation; 2.) Forces in homogeneous fields; 3.) AC electrophoresis; 4.) Orientation of non-spherical particles. For these effects to take place in vivo in animals or human beings certain conditions are essential which are not obtainable under the usual microwave exposures. For example, for pearl chain formation in the human body, freely movable particles of 30μ (diameter) or above will be needed, but particles of this size are not available in the body. Even if they were available then the microwave energy needed to produce the effect would cause overheating of the tissues. Similarly incident microwave fields of low energies will offer virtually no chance that any effect due to forces in inhomogeneous fields will be significant. For orientation of non-spherical particles to take place it has been ascertained that in vivo structures shorter than about 15μ will not be orientated by pulsed or unpulsed fields which do not overheat the tissues. It is unlikely that any histological structure exists which is superficial, sufficiently large and free to be oriented. Therefore, any significant biological orientation within human beings is very unlikely. As such, these reactions do not have any biological significance in the total competency of a given organism.[16]

To date then, the concensus of opinion is that the effects of microwaves on animals and man are mainly thermal—due to generalized or localized heating or due to thermal stress phenomenon. If there are any non-thermal effects—as has been suggested by some workers—they have not been proved beyond doubt.

OBSERVATIONS ON EXPERIMENTAL ANIMALS

Although experimental work on animals in this field has been going on for well over 15 years, standardized conditions have not been obtained in all cases. It seems that the biggest obstacle in this work has been the insurance of the desired flux density. The manner in which the experiments were conducted, animals exposed and the instrumentation leads one to believe that in all probability the animals involved were subjected to energy levels other than the reports indicated.

The main factors which influence the response of animals when exposed to microwaves are the frequency or wave length, time (period of exposure), irradiation cycle rate, air current, environmental temperature, position of the animal in influencing resonant conditions and standing waves, effect of reflections, difference in the sensitivity of organs and tissues and last but not least the type of animal used.

A number of experimental animals, chiefly mice, rats and rabbits have been employed for microwave studies. Dogs and a few monkeys have also been used.

The biological effects can be divided into those due to whole body or due to localized exposures of the animals.

Whole Body Exposures

When the whole body is subjected to microwave irradiation of high intensity the radiation absorbed is converted into heat and must be dissipated by various means at the disposal of the body. When these protective measures are insufficient to dissipate the heat as rapidly as it develops, the circulation of blood serves to spread the heat from the irradiated portions diffusely throughout the body, resulting in a rise of 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 leukocytes.[6, 9, 10] Severe hyperpyrexia carried to the point of death results in diffuse degenerative lesions throughout the body, including renal tubular degeneration, myocardial degeneration and necrosis, hemorrhagic lesions in the gut, respiratory tract, liver, and brain. Fatally exposed animals develop acidosis, hyperpnoea, and tetany, and finally die of respiratory arrest.[7]

Exposure of animals to microwaves of low intensity, which do not produce any appreciable thermal effect, lead to functional changes according to some Russian workers. These changes take place mainly in the nervous and cardiovascular systems (change in excitation and inhibition relationships in cerebral cortex, change in rhythm of cardiac activity, nature of ECG and so on). These changes were observed both with chronic and with single exposures and have been termed as non-thermal—specific—effects of microwaves.[5]

Localized Exposures

The eye and the testis are the two organs of the body most sensitive to microwaves.

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Eye—Localized microwave radiation at certain frequencies either continuous or pulsed, causes a rise in intraocular temperature and the formation of opacities in the lens. The characteristic lesion is a small, irregular or punctate subcapsular opacity, at the posterior pole of the lens after a latent period of several days to several weeks. Some of these opacities begin to regress after a while and within a few weeks disappear completely or leave small punctate scars. Another type of lesion, consists of grossly visible damage to other ocular structures such as the cornea, iris, and anterior chamber, as well as the lens. The lenticular lesion consists of subcapsular opacity which progresses rapidly and coalesces until complete opacification occurs.[2, 8]

Testis—The characteristic lesion found in the testis is a degeneration of the epithelium lining the seminiferous tubules, and a sharp reduction in the number of maturing spermatocytes in the lumen. There is patchy irregular distribution of damage within the testis, adjacent tubules often showing markedly different degrees of degeneration. The damage is almost certainly reversible except in severe cases.[4, 7]

Observations On Man

The observations made on human workers by U. S. and Soviet workers differ widely.

In the U.S.A. a large group of radar exposed employees along with a control group were put under a four year surveillance programme. During this period they underwent repeated physical and eye examinations. Detailed haematological and other laboratory investigations were carried out.[1] The examinations failed to detect any significant changes in the physical inventories of the subjects. The incidence of death and chronic disease, sick leave and subjective complaints was comparable in both groups. A high percentage of 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 with respect to radar exposures. In addition, only a small percentage of the exposed subjects had been aware of the heat or other subjective warning phenomena. Neither these tests nor subjective complaints are considered reliable indices of exposure.

An eye survey of a large group of microwave workers—both civil and military—has recently been concluded. Barring an occasional case of cataract in workers accidentally exposed to high microwave flux, the over-all eye findings in workers and an equally large control group were clinically insignificant. The extent of minor lenticular imperfection does not serve as a clinically useful indicator of cumulative exposure to microwave radiation. No relationship between lens imperfection and microwave cataract was found.[19]

The Soviet observers have conducted a series of examinations on their radar workers and control groups and their findings are as follows:—

Chronic irradiation under industrial conditions produces extremely polymorphic changes in the state of the human organism, causing functional changes in various organs and systems. The degree of their manifestation and the presence of characteristic symptoms are determined by the intensity and duration of the microwave influence as well as the individual peculiarities of the organism.[3]

The clinical syndrome is basically characterized by the presence of asthenia and vegetative reactions in a definite direction. The asthenic reactions such as headache, increased fatigability, increased irritability and sleepiness are not usually sharply pronounced, and have no distinguishing features. Similar observations have been made in a number of laboratories in the U.S.A. and United Kingdom.[11]

Cardiovascular changes such as arterial hypotension, bradycardia, sinus arrhythmia, lengthening of the conduction time in the heart, reduction of the amplitude of the spikes of ECG are noted.

The asthenic and vegetative reactions mentioned above are entirely reversible.

Intensification of the activity of thyroid tissue was detected in almost all the workers investigated by the Soviet authors. In some a small increase in volume of the thyroid gland was noted, however, clinical symptoms of hyperfunction of the latter were detected only in isolated cases.

In the Soviet Union cataracts that have a tendency to progress have been observed among microwave workers.[3]

DISCUSSION

During the last two decades thousands of persons have had long and short term microwave exposures during the course of their employment in military service or industry, many without protection. Concern over the effects of such exposure is natural and to be expected. But since the power output generated by radar and other electronic equipment was low enough it was not considered a serious hazard. The recent development of radar equipment with peak powers in megawatts and communications equipment with effective radiated power of several megawatts makes it necessary to evaluate the radiation hazard problem.

Experiments to date have been conducted primarily on small fur-bearing animals and under unusual test conditions. These animals have a high coefficient of heat absorption, a small body surface and a relatively poor heat regulating system. The human body by comparison has one of the best thermal regulatory mechanisms of all animal species and can readily adjust and maintain thermal homeostasis under severe stress conditions.

Conditions of radar operation and testing as compared with experimental conditions are markedly different. Humans are generally exposed while in free air and rarely to a stationary energised beam. Some radar beams are extremely narrow, and only a small portion of the human body is instantaneously exposed. The body can dissipate heat readily to the environment between such exposures. In view of the above, extrapolation of the results of animal experiments to human

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beings has a limited value unless inter-species and intra-species variability is recognized and carefully considered. It is beyond doubt however, that localized exposures of sufficient intensity and duration can produce microwave radiation injury in humans as evidenced by production of cataracts in a few microwave workers.

In the case of microwave workers, therefore, the real problem is that of avoiding exposure to unsafe flux densities. Towards this end a generally acceptable safe flux density has been established and microwave workers are educated to abide by certain rules. This procedure has been found to be very practical both in industry and under occupational conditions without jeopardizing the actual radar operation.

ASSOCIATED HAZARDS

Ionizing Radiation Hazard

The development of high-power equipment to produce greater radiated power densities has resulted in an associated problem—the production of ionizing radiation. The increased r-f power output of the equipment is frequently accompanied by variable amounts of ionizing radiation, mostly in the form of x-rays. The adverse effects of exposure to ionizing radiation are well known. Fortunately overexposure to this form of radiation is easily avoidable by proper shielding of equipment, educating the personnel and acquainting them with the precautions and control measures necessary to cope with this potential hazard.

Radioactive Material Hazard

A potential hazard exists in the form of radioactive materials used in components of electronic equipment, e.g., radioactive electron tubes which are commonly employed in modern microwave and radar equipment. It is important, therefore, for personnel working with such equipment to be aware of the possible dangers associated with radioactive electron tubes and to exercise caution when handling such tubes.

Fuel Hazard

High-powered radar and communication beams can produce sufficient heat in close proximity to cause ignition of volatile fuels leading to an explosion hazard to personnel and equipment such as aircraft. This problem exists mainly aboard naval vessels especially aircraft-carriers, because of limited space and a large number of communications and radar equipment. The refueling of aircraft and the location of fuel storage and handling facilities in proximity to equipment propagating radio-frequency energy create possible fuel hazards which must be fully evaluated in terms of safety of operations.

Ordnance Hazard

Information in this field is very limited but the possible hazard of inadvertent detonation of explosives due to sufficiently intense r-f fields, with the inherent dangers is appreciated. As in the case of fuel hazards this problem is especially important aboard naval vessels.

The solution for both fuel and ordnance hazard is to make the personnel aware of the conditions which may lead to mishaps and the general planning in the layout of various equipment to minimize the hazard consistent with operational efficiency.

Toxicity Hazard

For high power transmission through wave-guides certain gases under high pressure are being used as dielectric media, e.g., freon and sulphur hexaflouride. These gases can decompose and leak under certain conditions producing a toxicity hazard to the personnel. Again the personnel should be made aware of this problem and adequate ventilation should always be provided to keep the concentration of the leaking gases to a minimum.[17]

Safe Dose Level

Sufficient factual data is not available to determine the safe exposure level for each frequency throughout the microwave spectrum; therefore it was decided to select one satisfactory level for all microwave frequencies. A power density of 100 mw./cm.^{2} whole body or localized exposure has been shown to produce either hyperthemia or damage to organs such as eye or testis. Taking into consideration variables such as frequency of radiation, its penetration, and percentage of absorbed radiation, a safety factor of 10 was decided upon and the present exposure level of 10 mw./cm.^{2} was thereby established.[13, 18]

This safe exposure level of 10 mw./cm.^{2} is an average power level and not peak power. The safe time duration of exposure has not been defined so far. It has been suggested, however, that this power density is considered safe for either continuous, pulsed, or intermittent exposures.[15]

Exposure to electromagnetic radiation is but one of the several sources of heat input into the body. Body temperature depends on heat input such as high ambient temperature and physical labour and on heat dissipation capability as affected by clothing, humidity, etc. The added heat burden of electromagnetic radiation can be accepted satisfactorily to a certain extent by normal healthy persons but individuals who suffer from circulatory and certain other ailments are more vulnerable to such stress. The safe power level is appropriate for moderate environments only. Under conditions of moderate to severe heat and humidity the power level should be reduced by a factor of ten. Under conditions of severe cold higher power levels may be considered safe.[15]

Protective Clothing

Certain high-power radars have to be in 24-hr. operation, and their inoperative periods for maintenance, inspection and repairs must be kept to an absolute minimum. It is, therefore, likely that many main-

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tenance functions will be performed in outdoor areas exposed to dangerously high field intensities.

To meet the above situations protective suits have been designed for personnel. These suits, by means of reflecting the incident r-f energy, cause sufficient attenuation inside to make it safe for the wearer. Because of the nature of fabrics used the present suits severely limit the ventilation and perspiration of the user. Their utility, therefore, is limited to very cold environmental conditions.[12]

CONCLUSIONS AND RECOMMENDATIONS

Microwave energy poses a hazard problem to human beings. Although, to date, exposure to low energies over prolonged periods has not produced any significant ill effects in the personnel involved, there is no doubt that with the development and use of radars with many times the present power our entire concept of the biological potentials of this form of energy may be changed.

The injury caused by microwaves is mainly thermal. If there are any nonthermal effects they have not been proved beyond doubt. However, high peak energies of future radars may produce the latter effects also.

Based on present knowledge there is no cause for great concern or apprehension for the safety of the personnel involved in radar operations or the public at large, provided they are educated about the potential hazard and certain precautions are taken. At the same time we cannot afford to be complacent about it and neglect vigilance and search for possible ill effects.

Precautionary Measures

R-F Radiation—The following general rules should be observed to prevent unnecessary exposures to microwaves:

(a) The supervisory staff be made responsible for mapping out areas of unsafe power densities, i.e., above 10 mw./cm.,^{2} either by means of power density meters or by theoretical calculations. Appropriate warning signs should be posted. Ingress into the hazardous areas by personnel is to be permitted only under emergency conditions, and periods of exposure in these areas are to be kept to an absolute minimum commensurate with proper maintenance and operating procedures.

(b) Personnel are to be prohibited from working in the field of radiation of any energised antenna, wave-guide, feed-horn structure, or transmission line where the power density is unsafe.

(c) The practice of discharging into the surrounding area of r-f output of high-power generators is to be discouraged. Dummy loads, water loads or absorbent material are to be used to absorb the energy output of such equipment while being tested.

(d) Where test procedures require free-space radiation, the antenna is to be positioned so as to direct the radiated beam away from inhabited structures or other places where there are personnel.

Ionizing Radiation

The following general rules should be observed to prevent unnecessary exposures to ionizing or x-radiation:

(a) The supervisory staff ensure that all electronic devices on tubes capable of producing external x-radiation are properly shielded and the shielding is checked periodically for any leakage of radiation. Where shielding is not provided all such devices are to be operated in appropriate radiation-proof enclosures.

(b) Areas are to be checked by qualified experts to determine the level of ionizing radiation and, if found necessary, to establish time limits for personnel working in the area. Personnel working in such areas are to wear dosimetric devices and their exposures are to be recorded. The maximum permissible exposure to ionizing radiation is 0.1 rem/week.

Without producing any scare, the personnel should be made aware of the possible hazards of microwave and ionizing radiation and be educated in the observation of various ways and means to overcome the hazards.[17]

Medical Examination of Personnel

All microwave workers should undergo a preliminary medical examination. Persons having any cardiovascular deficit or any defect of the lens should not be accepted for this work.

Periodic medical examination of the personnel should be conducted yearly and the eyes should be subjected to detailed examination with ophthalmoscope and slit-lamp if possible.

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