Heating Characteristics of Laboratory Animals Exposed to Ten-Centimeter Microwaves

T. S. ELY, D. E. GOLDMAN, AND J. Z. HEARON

Summary—Experimental animals were exposed to a 10-cm microwave field in order to study the heating and cooling characteristics of the entire animal and localized sensitive structures. The flanks of rats, rabbits and dogs were exposed and the whole body heating was observed. After heating, the cooling curve was determined. Similarly, restricted area fields were used to study heating and cooling of eyes and testes. Data on the heating and cooling rates were used to determine the most sensitive structures. The experimental findings, together with the values for some pertinent related factors from the literature, provide the basis for an estimation of the possible risks to man from exposure to microwaves.

This paper originally appeared as a Naval Medical Research Institute Report (NM 001 056.13.02, dated March 21, 1947). It was prepared in response to a practical need for estimating hazards to personnel from exposure to microwave fields. Since that time the use of high powered microwave devices has continued to increase and, although there have been a number of studies directed to special aspects of the biological effects of microwaves, there has been little work published which deals directly with the over-all hazard problem. The authors feel that the report is somewhat "dated," but the editors hope that reprinting it will make some useful material available to a wider circle of readers than could have been reached with the limited Navy Report distribution.

Introduction

THE INCREASED use of microwave diathermy and of high field strength radar installations make it desirable to investigate some of the physiological effects of this form of energy. Although considerable work has been done on this subject, much of it does not lend itself to quantitative evaluation. The primary effort of this study has been directed towards the delineation of a hazard, and therefore certain facets of the problem have been given emphasis, while other areas, however interesting, have been bypassed.

The structures most likely to be damaged appear to be the body as a whole, the lens of the eye, and the testis. They have already been subjected to some study, and have been mentioned by Clark [1], Schwan and Piersol [4] and others. The lens and the testis owe their special sensitivity to their physical location relative to the body surface, their poor ability to dissipate heat, and in the case of the testis, high sensitivity to temperature increase. The body as a whole can tolerate only a moderate temperature increase, and has a limited ability to lose heat. It is less able to lose heat by convection, radiation, and evaporation to the surroundings, for instance, than a small, well vascularized area of that body would by conduction and bloodstream convection to the remainder of the same body. Although the lens tolerates relatively high temperatures, the eye is completely avascular in the lens and vitreous, therefore leaving conduction through the humors essentially the only route of heat loss. The testis is extremely sensitive to elevated temperature. Other localized areas of the body are relatively less sensitive to 10-cm microwaves by reason of being less temperature sensitive, being deep enough to avoid most of the energy, having a better vascular or conductive pathway for the loss of heat, or a combination of these factors. The undesirable effect of excess temperature in each of these three sensitive structures, the whole body, the eye and the testis, is, respectively, heat disablement, lenticular opacity and tubular injury.

As the investigation progressed, it became apparent that in all but rather restricted circumstances, the testis was the limiting factor with regard to hazard. Therefore the greatest effort was made on the study of this organ.

The 10-cm wavelength is important because of its biologically "in-between" position in the electromagnetic spectrum of radiant energy. Substantially longer wavelengths penetrate deeper, and are absorbed more diffusely by animal tissues, and are therefore less likely to produce small regions of differential heating. Energy of significantly shorter wavelength has very little penetration, and approaches the infrared in behavior. Radiant energy in the 10-cm region of the spectrum can penetrate tissues sufficiently to avoid concentrating heat production in the region of skin receptors, and may produce undesirable temperature elevations below the surface.

For the purposes of this study, we have made the assumption that the entire effect of the microwave radiation on biological material is the production of heat. While not excluding the possibility that some "athermal" process may exist, we have had no reason, in any of the work, to believe that anything but a thermal effect is involved. This view is supported by other workers in the field, *e.g.*, Clark [1], and Schwan and

Manuscript received June 9, 1964. The opinions or assertions contained herein are the private ones of the authors and are not to be construed as official, or reflecting the views of the Navy Department or the Naval service at large.

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Piersol [2]. Williams, *et al.*, point out that the photon energy in this band of microwaves is only about 1/3,000,000 that required to produce ionization in tissue [3].

It has been assumed that for a given experimental setup, the heating rate is proportional to the field intensity, and independent of time or temperature. Heating rate change would depend on a change in dielectric characteristics which would be minor. In the case of the eye and the testis, the further assumption is made that cooling rate is proportional to the temperature rise of the part, as opposed to other limited areas of the body, (*e.g.*, the thigh), where Herrick and Krusen have found that cooling is markedly influenced by a thermally induced increase in blood flow [5]. Since the eye has no vascularity in the region of the greatest heating, alteration of cooling rate by blood flow change is remote and secondary. The testis is limited in blood cooling capability. In addition, for testicular temperatures below body core temperature, an increase in blood flow would heat rather than cool the organ. Experimental support for these two assumptions is illustrated by Figs. 9 through 13, and is explained in the Appendix.

The whole body, which undergoes a considerably more complex physiological adjustment with increased temperature, follows a much more involved cooling pattern, and in addition experiences a change in metabolic heat contribution.

The cooling time constant (τ) was estimated usually by replotting the cooling curve on log-linear paper. It was checked in some cases by plotting the heating curve in a similar fashion, and in some cases by timing the heating interval required to produce a given temperature rise. The Appendix develops the relationship

$$\ln\left(1 - \frac{I'}{I}\right) = \frac{-t}{\tau}$$

which is used in estimating τ by this last method. Since this more closely represents the practical situation, it was used as a check.

Much of the quantitative data of the study involved the determination of the field required to maintain a prescribed temperature elevation of the structure under consideration under steady-state conditions (I'). Field intensity could have been controlled in several ways. A method which proved very convenient, mainly because it lent itself readily to automatic control and accurate measurement, was that of "on and off" cycling in response to the temperature of the subject. Since the temperature variation was very small with respect to total temperature rise (ΔT), the cycle time was much shorter than the time constant of cooling and thus the time average field could be used as the field intensity.

A portion of this study concerns itself with the determination of the microwave power absorbed by the animal to a profile exposure. For the purpose here, it is represented by the percentage of the power in the area of the animal profile determined under free field conditions which is absorbed and appears as heat in the animal. This absorption is determined from the initial slope of the heating curve. The values obtained are not directly comparable to true absorption efficiencies, such as those of Schwan and Li [6] principally because less than the entire animal surface presented to the microwave beam was perpendicular to it, and because of the appreciable effect of beam diffraction where the subject's dimensions are not very much greater than the wavelength used. Hence, the term *absorption "efficiency,"* as used here, is a qualified figure.

Because one of the principal factors in this study was the rate of heat dissipation, the ambient conditions were of direct importance. During the experimentation, dry bulb temperatures were approximately 24°C, radiant environment that of the dry bulb, relative humidity about 50 per cent and air velocity essentially that due to convection only. In the application of the data to practical situations, ambient conditions form a direct and important factor.

In the evaluation of the critical temperature and critical field intensities, *any demonstrable damage* was used as the criterion. It was felt that if this resulted in an error in the estimation of threshold values, the error would be in the safe direction. In the case of the eye, opacity formed the basis of calculating a critical temperature, even though a small opacity may be asymptomatic. For the testis, mild tubular epithelial injury is certainly a reversible process. However, the study of damage rate, recovery rate and their interrelationships is another large field, and was not included in the scope of the study.

Most of the results have been presented in the form of a relationship between effect and field intensity, *i.e.*, power per unit area or milliwatts per square centimeter. This seemed to offer the most direct relationship of cause and effect. Heat gain and loss are both closely related to surface area, consequently this area factor is largely cancelled out. In a practical situation also, field intensity is the quantity which is measured, and biological result the quantity of interest.

Materials and Methods

Fig. 1 is a block diagram of the major equipment used. An electronically regulated power supply provided a transmitter input sufficiently stable to achieve an average microwave output which was constant to within one per cent with time. The microwave generator was a high power pulsed military radar transmitter, having a frequency of 2880 Mc/sec, or 10.4-cm wavelength, which is in the "S" band. The microwave power output was passed through a waveguide into a directional coupler which had a coaxial output attenuated 40 db. This greatly reduced power was then further attenuated by a coaxial attenuator pad, and measured with a Hewlett-

Packard 430-C microwave wattmeter. Total power output of the transmitter could therefore be determined from the wattmeter reading. The directional coupler led into a power divider, which permitted continuously variable division of the power between the transmitting horn and a water cooled load. Field strength could be reduced to any desired degree, or the entire power could be shifted into the water load for calibration purposes. The horn radiated the microwave power into space providing a divergent field with vertical polarization. In the illustration, the subject is shown much closer to the horn than was usually the case.

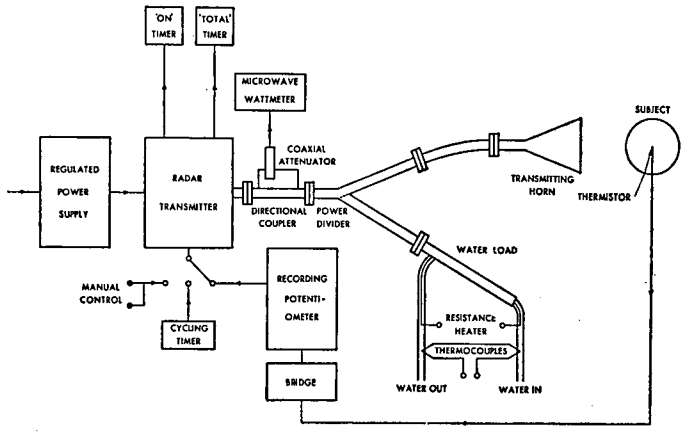


Fig. 1.

Three methods were used for on and off control of the transmitter, manual, time cycling and temperature cycling. The great majority of the work was done with the last named method of control. For some work where it was desired to reduce the field rapidly by an accurately known amount, time cycling by a synchronous variable sector cam timer with a speed of three rpm was used.

Two synchronous timers were used to determine the time average of transmitter "on" time. One determined the total time during a specific exposure interval, and the other, which operated only with the microwave power, indicated the accumulated "on" time. Temperature controlled cycling was relatively slow, so that small starting and stopping errors of the timer were negligible. However, for the time controlled cycling, where very numerous and frequent starts and stops occurred, in order to prevent a cumulative starting and/or stopping error, the individual microwave pulses were counted electronically, and the time average power computed from the total pulses counted.

All of the microwave equipment and the subject were contained in a commercial prefabricated double copper screen shielded room. A microwave absorber lining the room provided a relatively anechoic chamber in order that the field pattern be undistorted by reflections. Measurements of standing wave ratios in the room demonstrated a satisfactorily low reflection of about ± 0.1-db power standing wave ratio.

Field Calibration

The water load was provided with a resistance heater for use on low-frequency power, and thermocouples in the water inlet and outlet in order that the temperature rise of the water passing through could be measured. A determination of the standing wave ratio of the complete water load indicated that it was an efficient absorber of microwave power. The first phase of field calibration was the determination of microwave power output of the transmitter. For this purpose, a constant flow of water was passed through the water load. The water was heated by one of two sources. First, heating was accomplished by diverting all of the microwave power into the water load. Temperature rise was recorded on a recording potentiometer. Microwave power was then turned off, and simultaneously house current supplied to the resistance heater. This was varied by an adjustable transformer until the temperature rise matched that produced by the microwaves, and the corresponding power level was read on a wattmeter in the line. The actual temperature rise of the water and its rate of flow provided a third determination of power. Measurements made by the three methods were in good agreement.

In order to find field strengths, it was necessary either to measure the field directly, or to determine the field distribution for a known total radiated power. The former method is beset with many difficulties, and it proved more practical to use the latter. This was done using a small receiving horn, attenuators, the microwave wattmeter and a recorder. The system, while it did not yield absolute values, did behave as a linear system, and was entirely satisfactory for relative measurements. The receiver, automatically scanning the beam in a plane perpendicular to its axis, recorded families of curves which were then transposed to the form of contour plots of field intensity in planes at several ranges. A sample distribution plot is shown in Fig. 2. The field distributions so obtained were in excellent agreement with those calculated from horn geometry. Absolute field strengths were then calculated from the total microwave power, field distribution, and of course, average "on" time when cycling was used.

The animal exposures can be divided into two groups, those in which a large area of the animal was exposed to the beam, and those in which a relatively restricted area was exposed. The "whole body" exposures constitute the first type, and the eye and testicular exposures the second. *Profile area*, that is, the lateral area of most experimental animals, and the frontal area of a human, probably represents the largest area likely to be exposed in the practical case. Greater area is possible, but not without multiple sources, or unusual reflection. Five rats having a weight in the range of 200–300 grams, 10 rabbits in the range of 3–4 kilograms, and 9 dogs in the range of 8–20 kilograms were used in these large area exposures.

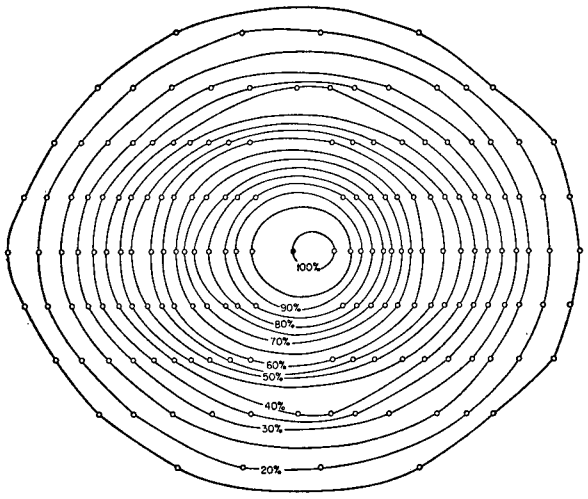


Fig. 2.

For the restricted area, or localized exposures, radiation was limited as far as possible to the area of direct interest, in order not to confuse the determination with any more general body heating than possible. During these limited area exposures, the axis of the animal was oriented parallel to that of the beam, thus reducing the intercepting area considerably, and the appropriate end of the animal passed through a hole in a batt of microwave absorber. This limited diffraction of the beam, and absorption of any irregular field by the remainder of the animal. "On" field strengths were limited to about 100/mw/cm^2 in most cases, in order to minimize differential heating. Eight rabbits and one dog were used in eye heating experiments. Fifty dogs and three rabbits were used in the testis experiments.

Animal support structures were constructed of low-loss materials of thin dimensions. Plastics, glass, cotton and nylon were the principal materials used. Wood, although having greater loss, was used sparingly in regions of lower field intensity. For the whole body exposures, the rats and rabbits were supported in a tube of plastic insect screen suspended from a polystyrene rod, which was supported on glass tubes. The dogs required a somewhat stouter support consisting of a canvas sling, a polystyrene rod and wood uprights. These uprights were in a region of reduced field intensity, and were oriented to present only the edge to the beam.

General anesthesia would have been useful in the whole body exposures in order to provide immobility. However, it was found that any of several general anesthetic agents tried caused a profound fall in body temperature which badly confused the experiment. The rats and rabbits proved relatively unaggressive during exposure, and were exposed without medication. Dogs, however, if exposed without anesthesia, often became quite active, with a resulting additional metabolic heating which confused or completely obliterated data from microwave heating. It was then found that premedication with 6 mg/kilogram of chlorpromazine 1 hour before exposure reduced the activity of the dogs and permitted the collection of useful data. This drug did not result in temperature depression sufficient to influence the data significantly. Results with the chlorpromazine compared favorably with what useful data were obtained from the unmedicated animals.

For the localized exposures, general anesthesia could be used, since exposure times were, in general, shorter, and body temperature was not directly the quantity of interest. The limited area of exposure and the use of general anesthesia simplified the support problem. After the animal was anesthetized, he was placed parallel to the beam axis on a table of appropriate height, with the proper end directed towards the antenna. A 2-foot square of the microwave absorber material having a hole in the center was placed over the exposed end of the animal in order to shield the support and the remainder of the animal.

Temperatures were measured with thermocouples and thermistors. These were of two types, those mounted in needles for interstitial measurements, and those in flexible catheters for rectal measurement. Thermocouples were used for a minor segment of the study, principally for differential measurements using multiple points recorded concurrently, on a 6-point recording potentiometer. In this application, thermocouples were advantageous in that they all had the same sensitivity and range. Thermocouples, however, are relatively insensitive, and require a reference junction. Also, it was inconvenient to change the range and sensitivity of the associated recording equipment.

Thermistors were used for the bulk of the work, since most of it consisted of single point recording on a continuous line recorder. With thermistors, range and sensitivity could be changed easily and rapidly, and the high output permitted much higher sensitivities and accuracies. A small thermistor bead sealed in a short 2-mm diameter glass rod was used in a catheter for rectal temperature measurement, and a very small thermistor mounted inside the tip of a 24-gauge needle for the eye and testicular determinations.

The thermistor was connected as one arm of a direct current unbalanced bridge, the output of which drove a 3-mv recording potentiometer. Precision variable resistors in the bridge permitted the rapid changing of range and sensitivity. Bridge balance was set at the hot end of the scale, and maximum unbalance at the cold. By this mechanism, the nonlinearity of the thermistor was almost completely compensated by the nonlinearity of the bridge, resulting in a recorder scale which was linear with temperature within very small error.

Thermistors were calibrated against a National Bureau of Standards certified mercury in glass thermometer. The thermistor recording system had a sensitivity of about 0.01°C and an accuracy of about 0.05°C.

Whole body temperature was measured rectally. This is the best single index of the core temperature according to Hardy [7]. Although the average body temperature (which would have been the most desirable quantity to determine) is lower than the rectal temperature by a significant amount over the relatively

large temperature increases used, and since it was an increase rather than a decrease where greater body differentials would be expected, it was assumed that a change in rectal temperature reflected a change in average body temperature sufficiently closely.

During the localized eye exposures, temperature was measured with the 24-gauge needle thermistor at the posterior pole of the lens. For this wavelength band, this location has been shown to be that of theoretical and actual maximum temperature development in the eye and the site of opacity production by Salisbury, *et al.* [8], Richardson *et al.* [9], and others. Rabbits were used for all but one of the eye experiments. This species was used for the same reasons of others in the field, mainly, the similarity of size and shape between the rabbit eye and the human eye.

Testicular work was carried out mainly on the dog, since this species was available, and had testes comparable in size and shape to the human organ. Testicular temperature was measured about 1 cm from that surface nearest the microwave source. By experimentation with high field intensities it was found that this was approximately the location of greatest temperature development. Testicular temperatures were found to equalize throughout the organ with relative rapidity, and with the low field intensities used it was found, by multiple point recording, that differential temperature development within one testis was small. It was also found, that with symmetrical orientation of the testes, temperature rise in each was essentially the same. This fortunate fact allowed the simultaneous heating of both testes, temperature measurement in one, and biopsy of the other which was untraumatized by the thermistor needle.

Experimental Procedure

For the bulk of the experimental runs, the following general sequence was used. The animal was weighed and premedicated (in the whole body exposures), and placed in the appropriate support. The thermistor or thermocouples were inserted and, in the case of the whole body exposures, the profile determined. Temperature recording was started. Fig. 3 illustrates the series of events. After a period sufficient to give a good initial temperature value, the microwave power was turned on which caused heating of the particular structure under study.

When the temperature reached a predetermined level, automatic cycling occurred in response to temperture. This was allowed to continue until many cycles had been produced, and a stable steady-state field intensity could be calculated. Usually, then, the control point was raised by an integral number of degrees, causing further rise in temperature to the new control level. Following the determination of steady-state field intensities at one or more temperatures, the microwave power was shut off completely, and cooling was allowed to take place.

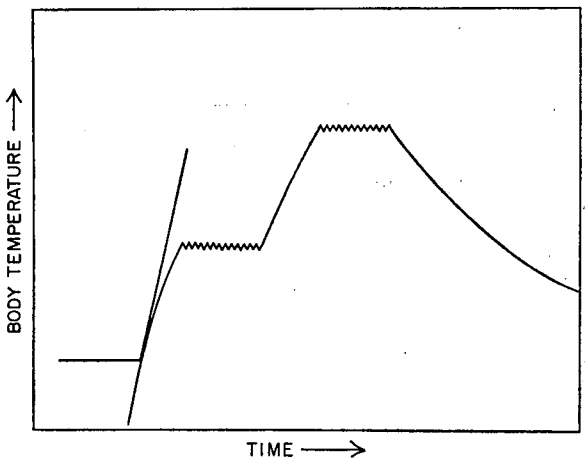


Fig. 3.

Results

Fig. 4 shows the absorption "efficiencies" calculated for several animals of three species, and the mean of the values for each species. In order to obtain a rough evaluation of the effect of fur on the absorption of microwave energy, a small series of dogs was exposed before and after clipping. Average "efficiency" before clipping was 33 per cent and after clipping was 35 per cent, this difference not being significant.

In Figs. 5 through 7 are plotted the steady-state values of field intensity required to maintain a given body temperature for whole body exposures of rats, rabbits and dogs.

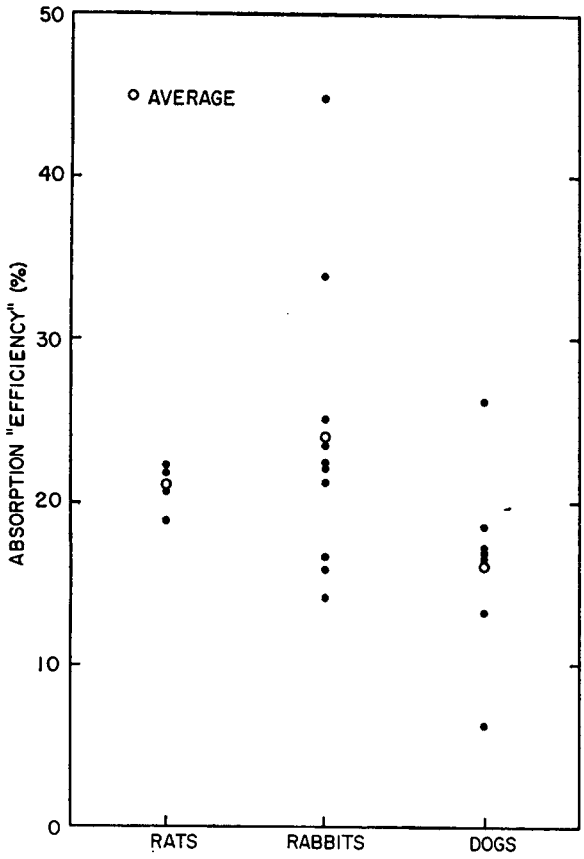
Fig. 8 shows approximate composite minimum field intensities for each of the three species.

Most animals of all three species survived a maximum temperature of 42°C, for this relatively short exposure, which was generally less than an hour at maximum temperature. Roughly half survived 43°C maximum, while 44°C proved uniformly fatal. It was our experience that if the animal did not die during or within a very few minutes of the exposure, survival was the rule.

Fig. 9 shows the steady-state field intensities of the eye exposures. One dog eye is represented, the reminder being rabbit eyes.

Cooling time constants (τ) for the eyes were all within the range of 100 to 180 sec. In several cases, τ was also computed from the heating curve, and agreement was good in most cases. Two eye cooling curves are shown in Fig. 10.

Fig. 11 shows steady-state field intensities obtained on a very limited number of rabbit testes. Although the results are entirely consistent with those of the dogs, rabbit work was not continued since the size of the rabbit testis is much smaller than the human. Fig. 12 shows the dog testis steady-state field intensity results. Since 35 dogs were used in this particular testicular series, the graphs are plotted with mean, standard deviation and minimum field for each temperature rather than individual lines. Of course, in the actual temperature plot, the first set of values represents the mean, standard deviation and maximum initial temperature. Cooling



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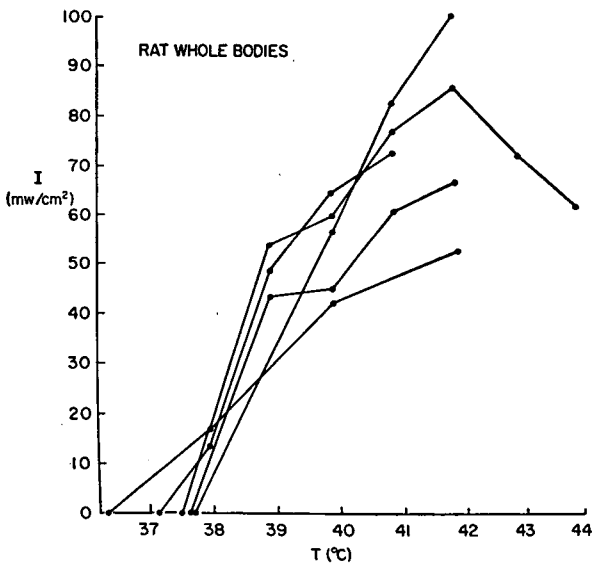

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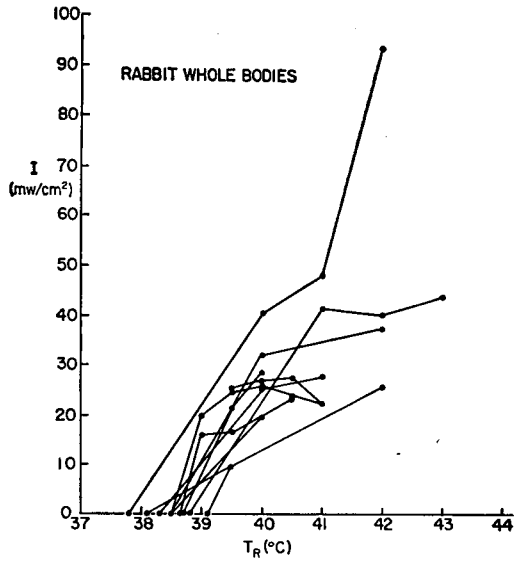

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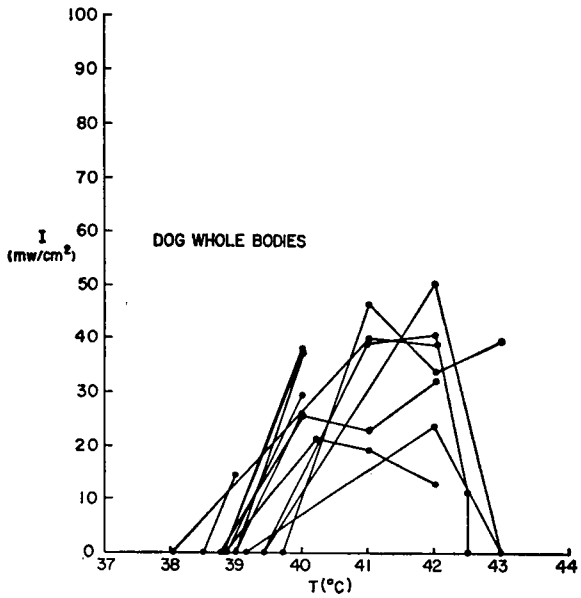

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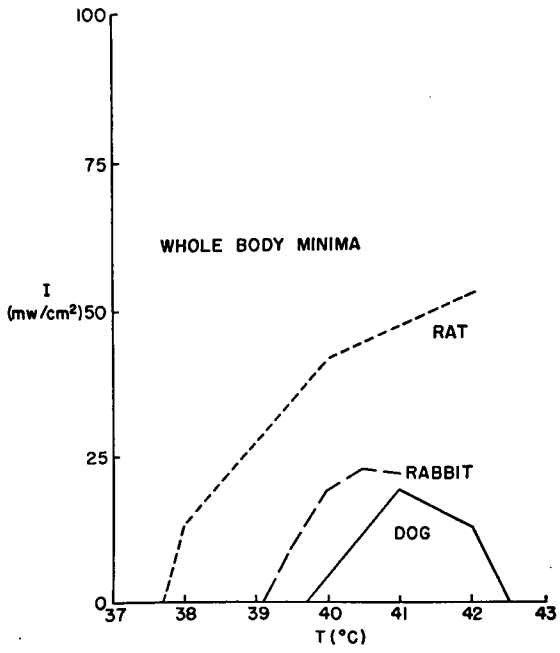

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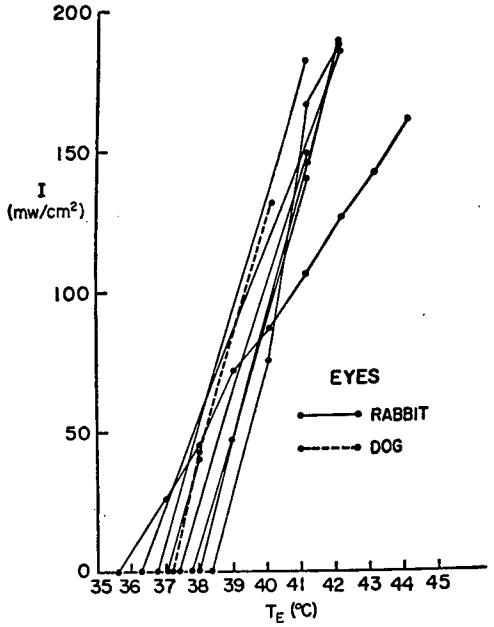

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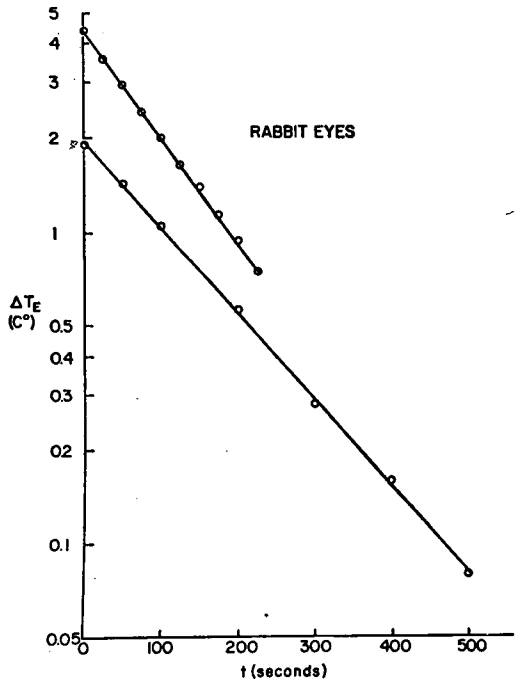

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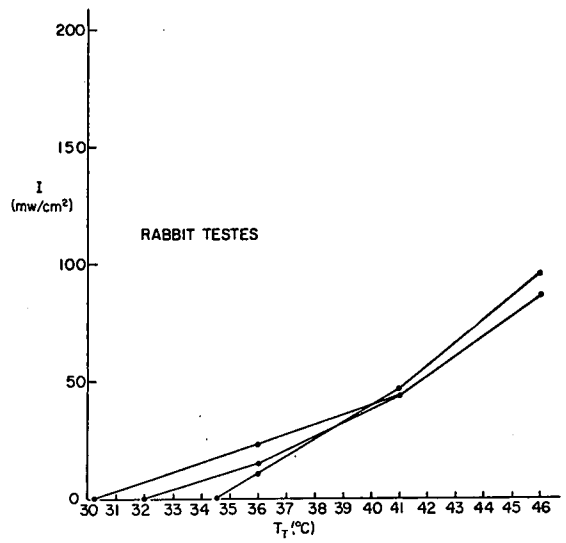

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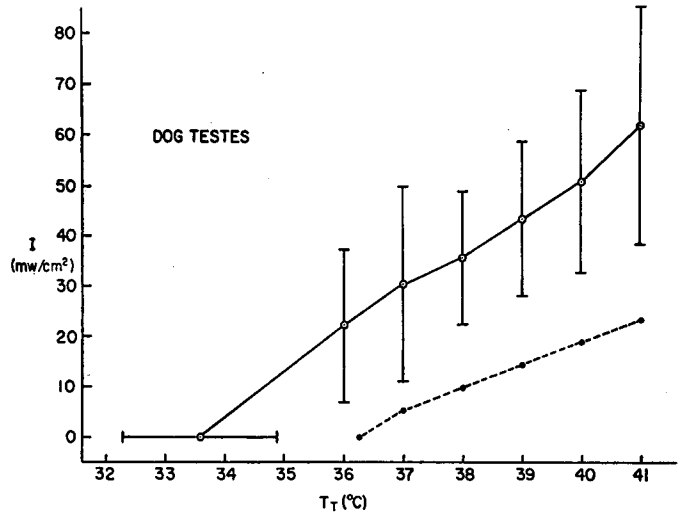

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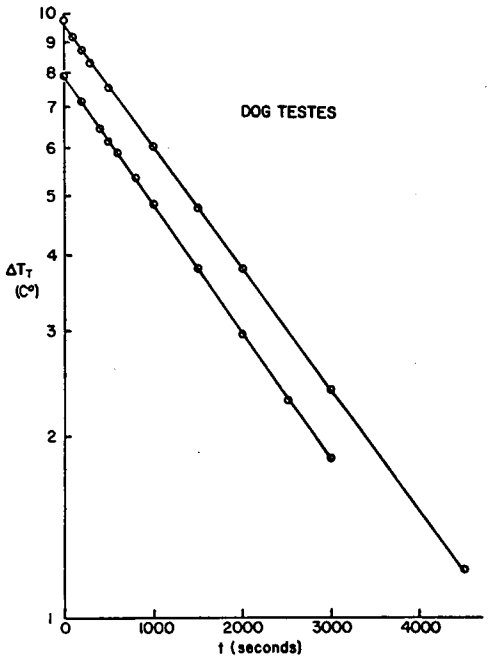

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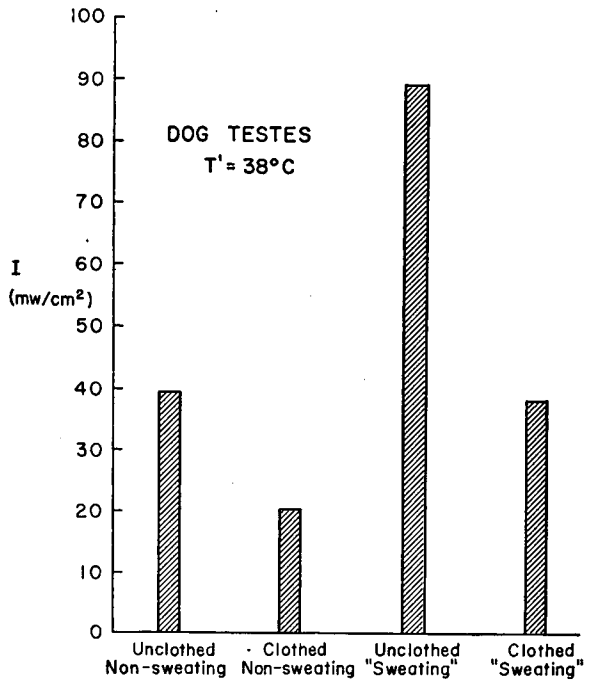

Fig. 14.

curves of two dog testes are shown in Fig. 13.

Fig. 14 shows the results of a series of dog testes which was done on eight dogs in an effort roughly to evaluate the effect of clothing and sweating neither of which the dog has, but both of which are usually possessed by the human. The mean fields required to maintain a testicular temperature of 38°C were determined for neither, clothing only, "sweating" only and both. The use of simulated clothing in this case was a straightforward procedure; an attempt was made to achieve a representative thickness and tightness. Simulated sweating was accomplished by wetting the scrotum with prewarmed water, and maintaining this wet condition by a small flow (an occasional drop) of warmed water through a small polyethylene tube. As would be expected, clothing decreased the equilibrium field required to maintain 38°C and "sweating" increased it. When clothing and "sweating" were used together, the results were quite comparable to those when neither was used. This was particularly true of the mean value but the individual dogs were reasonably close also.

Discussion

As has been mentioned, we have chosen to use any demonstrable damage as a criterion of hazard. In addition, the most sensitive individual in a group has been used in the evaluation of results, since it would be desirable to avoid injury to en entire group rather than to some segment of it. Individual differences are considerable, as evidenced by the experimental results.

The whole body exposure results (Figs. 5 through 7) clearly show the failure of cooling mechanisms at the higher temperatures, particularly in the case of the dogs. At increasing body temperatures in these animals, cooling reaches a maximum limit, and beyond this undergoes a failure presumably due primarily to a central failure of the respiratory mechanism. Also, metabolism is increased under these conditions, partly because of specific temperature dependence, and partly because of an increased respiratory effort.

Examination of the curves shows that, at the lower elevations, the slopes for the three animal species were roughly the same. At the higher temperatures, a reduction in slope occurred with a few of the rats and rabbits whereas, with the dogs, this tendency was quite evident. The curves for three of the dogs actually returned to the abscissa, where body temperature was maintained at the elevated level by metabolism alone.

As a preliminary to a proposed series of human whole body exposures, two such exposures were made. Since the human profile was comparatively large, the field intensity was quite low at the extremes as compared with the center. Exposures were frontal, with appropriate eye and testis shielding. The first exposure was to a field of 100 mw/cm^2 in the center, a total power of approximately 250 watts in the profile area, and an ambient temperature of 24°C. The exposure lasted 48 minutes, during the course of which rectal temperature dropped 0.4°C. In an attempt to produce hyperthermia, a second exposure was made with about the maximum capability of the apparatus, an intensity of 220 mw/cm^2 in the center, and about 400 watts over the profile. Ambient temperature was 25°C. This exposure likewise lasted 48 minutes, and resulted in a rectal temperature drop of only 0.15°C. The rectal temperature drop does not rule out a rise in average body temperature, since a reduction in normal differentials could account for both events. However, it was obvious, from this limited human exposure, that the subject was in good thermal control with mild sweating, and without a rise in core temperature and that further experimentation would require considerably more field intensity.

In order to formulate an approximate human whole body hazard, it is necessary to have some figure for maximum heat dissipation ability. This would, of course, depend on many other factors. However, a nominal value of 1000 watts is given by Schwan and Piersol [4], and 800 watts by Bazett [10]. Other similar values may be found in the literature. It is important to realize that this value of maximum heat dissipation depends on many related factors, principally air speed, temperature and humidity, other radiant environment, metabolic rate, clothing, beam, geometry and time. It is quite reasonable to consider the individual who is working hard in a reasonable amount of clothing on a hot, humid, still day under the noontime sun, who is on the verge of heat disability, and whose microwave heat input tolerance would be zero.

Schemes for the evaluation of a particular situation with respect to the above factors have been formulated. Belding and Hatch [11] provide a set of charts which can be used for a graphic solution.

The one dog eye exposed was at least consistent with the rabbit results. In Fig. 9, the rabbit eye which appears the most sensitive is noted to have the most experimental points. The entire experiment for this rabbit took considerably longer than for any of the others, and the apparent sensitivity is probably due to a concurrent heating of the head of the animal. In this animal then, sensitivity appears to be a function of heating time to some extent. In the human, this factor would be much less pronounced because of the better heat dissipation of the whole body.

In addition to knowing the dependence of eye temperature on field intensity, it is necessary to know the relationship between eye temperature and the production of injury. Several studies have been done on this subject. Williams, *et al.* [3], found that a temperature of 49°C at the posterior pole of the lens in the rabbit is threshold for a single 25 minute exposure, and that 53°C was threshold for a single 5 minute exposure in the same situation. Richardson, Duane, and Hines [12] found some opacities in the rabbit following a single exposure in which the posterior pole of the lens reached 52°C. They found no opacities when multiple exposures

were given under conditions which produced a temperature of 47.1°C. After a review of these and other investigators, Schwan and Piersol [4] have suggested a human threshold eye temperature of 45°C.

A preliminary evaluation of the relative sensitivites of the three structures in the human will be made now. Experimental animal data are used, and the pitfalls of this maneuver are acknowledged. Estimates of the initial temperature, the maximum permissible temperature, the corresponding temperature rise, the field strength necessary to maintain that temperature rise and the time constant of each of the structures in the human are listed in Table I. Initial rectal temperature is considered 37.0°C. Maximum permissible rectal temperature is listed at 39.0°C (102.2°F), although this is somewhat arbitrary. This represents a temperature rise of 2.0°C. From the whole body experimental animal data this amount of temperature rise can be maintained by a field intensity of about 20 mw/cm² in the most sensitive individuals. However, under average conditions the human is able to dissipate heat at a considerably greater rate than these laboratory animals, principally because of the sweating mechanism. Field strength required to maintain a 2.0°C temperature rise in the human has been estimated at 100 mw/cm². This is based on a somewhat standardized man of 70-kilogram weight, 2.0 square meter total body area, 1.0 square meter profile area, 100 per cent absorption efficiency, 0.83 specific heat, 1000 watts maximum heat dissipation ability above metabolic rate, and essentially even distribution of temperature increase, at rest in average ambient conditions.

TABLE I

Structure	Initial Temp. (°C)	Maximum Temp. (°C)	Temp. Rise (°C)	Steady-State Field (mw/cm²)	Cooling Time Constant (sec)
Whole body	37.0	39.0	2.0	100	(50 joules/cm²)
Eye	37.0	45.0	8.0	155	100
Testis	35.6	37.0	1.4	5	250

The maximum profile area estimate is the limiting case, and is used only for simplicity. A somewhat closer estimate might be $1/\pi$ of the total area. The 100 per cent absorption efficiency is also a limiting case, but Schwan and Li [6] have shown that absorptions of close to this are possible theoretically. The maximum heat dissipation ability is a simplified round number mentioned previously. Although direct use of the fact is not made in the curve to follow, it is significant that this level of heat dissipation is associated with a rectal temperature of about 39°C in the steady state under average circumstances [10]. A time constant could not be used for the human whole body, since cooling rate is a complex function, only partially dependent on rectal temperature. This is true of the human, with his very effective sweating mechanism even more than of the non-sweating animals used in the study. The thermal mass of the body in terms of profile intake intensity has therefore been given rather than τ. This also is based on the assumptions above.

Human eye temperature at the posterior pole of the lens has been estimated as equal to the rectal temperature. This certainly is a maximum, and is probably somewhat lower in actuality, as evidenced by the rabbit data. The maximum permissible eye temperature given is the 45°C value suggested by Schwan. For the resulting temperature rise of 8.0°C, a field intensity of 155 mw/cm² has been chosen, based on the most sensitive rabbit eye in the present study. The time constant τ was also chosen from the present study, and represents the most sensitive condition (smallest value).

For the testis, an initial temperature of 35.6°C was used, as this is the maximum human normal found by both Badenoch [13], and Newman and Wilhelm [14], of which more will appear later. The threshold temperature of 37°C was the lowest damaging temperature found in the present study. The field intensity required to maintain a threshold temperature was chosen from the most sensitive of the dog series at 5 mw/cm². It is of considerable significance that this is about the same figure that would result if computation were based on the 1.4°C temperature rise rather than the actual temperature of 37°C. Although time constants varied widely, and bore some relationship to I', a time constant of 250 sec was used as representative for this preliminary evaluation. Further evaluation of the testicular sensitivity will be made later in this report.

Fig. 15 is a plot of whole body, eye and testis thresholds from the values in Table I. Any point on the line for each structure represents the time necessary to produce the specified temperature rise at a particular field intensity under the conditions already stated, or conversely, the intensity necessary to produce the temperature rise in a given time interval. The early, short time, portion of each curve approaches the conditions of no cooling, approaches the hyperbola which is proportional to the heat capacity. The long time condition represents the steady state where heat input is balanced by heat output, and becomes a constant value of field intensity. The central portion of the curves represents the transition between these two conditions, where significant cooling occurs, but before this cooling reaches the rate of heat input.

Graphic presentation for the eye and testis is directly from formula (13) of the Appendix. Since heat loss from the whole human body is not a simple function of its temperature rise, a complete smooth curve was not drawn. The hyperbolic portion was taken from the 50 joules/cm² figure of thermal mass, and the late portion of constant field intensity from the heat dissipation ability. These curves were extended with dashed lines to intersection although, in fact, there would probably be a smooth transition as in the case of the eye and the testis, somewhat above the dashed portion. This

dashed line, then, is in error in the safe direction.

A factor of significance at the shorter times, and affecting mainly the consideration of whole body heating, is that of the time of heat distribution. Since absorption is essentially all in the first few centimeters of tissue, and the above calculations are on the basis of even distribution of heat throughout the body, the whole body curve at short times would undoubtedly shift to another hyperbolic segment with smaller constant representing the heat capacity of the volume which is heated directly, and probably somewhat larger permissible temperature rise. This consideration applies to a much less extent to the localized exposures, where biological effect is essentially at or near the site of heat generation, and heat distribution is consequently much less a factor.

These curves are simplified, depend on many assumptions and are only approximate. They are, however, bases for some general observations. It appears that for a short exposure the eye is more sensitive than the whole body because of its smaller thermal mass. At longer times, the whole body appears to be more sensitive than the eye principally because of its lower critical temperature. It also seems justified to assume that the testis is considerably more sensitive than either of the other structures.

To develop information of significance to the human species, a further evaluation of the testicular situation was indicated. Two unknowns immediately present themselves; what is "normal" human testicular temperature, and what is a threshold hazardous human testicular temperature? The literature on this subject was reviewed in an effort to supply an answer for each of these questions. An experimental approach to either was outside the scope of the study.

The most useful studies of "normal" temperature were those of Badenoch [13], and Newman and Wilhelm [14]. In both studies general, spinal and local anesthesia were used alone or in combination. Only those cases under local anesthesia were used for the present evaluation in order to avoid the likely effects of spinal or particularly general anesthesia on the measured temperatures. For the former study this involved 16 young men with a mean age of about 27 years and, for the latter study, 11 older men with a mean age of 61 years.

In Badenoch's series, peritoneal and scrotal temperatures were measured, rather than rectal and testicular. It is felt, however, that these should be roughly equivalent. Data from these two series, plus that of the present study, are plotted in Fig. 16. For each item, the range from minimum to maximum, the standard deviation and the mean are indicated.

It appears that the ambient temperature of the present study was between that of the other two series. The deep temperatures measured in the two human series are essentially the same, while that of the dogs naturally is higher. The mean testicular temperature of the dogs,

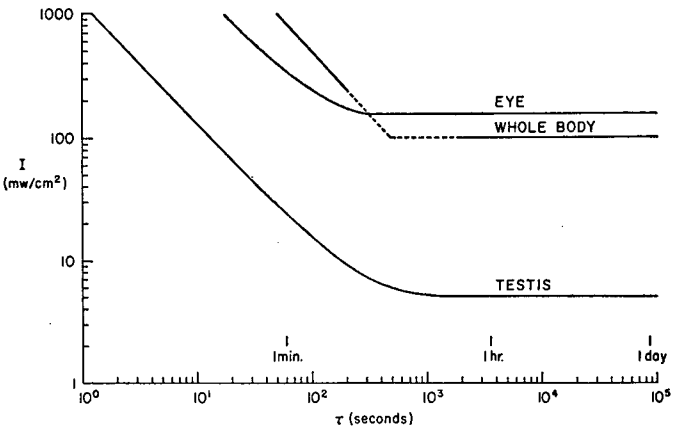

Fig. 15.

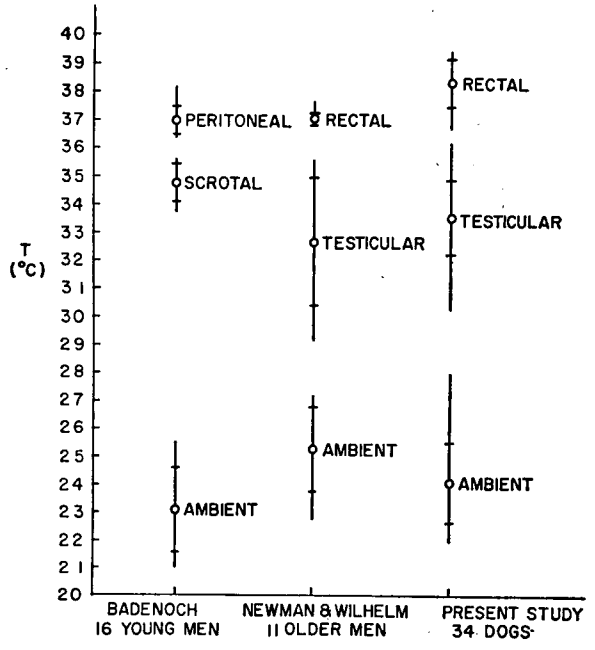

Fig. 16.

however, falls between the testicular temperature of the Newman and Wilhelm series, and the scrotal temperature of the Badenoch series. It is interesting to note that the maximum temperature of both of these two items in the human series was 35.6°C. It is also interesting that in the series of Badenoch, the individual having the highest scrotal temperature had the lowest peritoneal temperature, with a difference of only 0.8°C. The highest initial dog testis temperature is higher than that of either human series.

"Normal" testicular temperature would appear to vary considerably from individual to individual and, despite the thermoregulatory ability of the scrotum, even in one individual from time to time. Such factors of environment as confinement by adjacent areas of the body or clothing, hot and humid air, and hot water could prevent the testes from being cooler than the body, and even raise their temperature above that of the body. Fukui [15] discusses the effects of clothing and hot water, and points out that the propensity of the Japanese for taking hot baths involves an exposure of

about 30 minutes to water of from 40° to 46°C. Testicular temperature surely approaches water temperature in this case. The only significant cooling is by the meager circulation to the rest of the body, which itself undergoes considerable hyperthermia under these conditions. It may be that such factors cause human testes to sustain a certain amount of thermal damage and repair repeatedly throughout life, as a normal course.

The evaluation of a temperature threshold for testicular damage is a rather difficult problem. It is undoubtedly a function of exposure time, and probably also age. Several authors have demonstrated testicular damage following experimental cryptorchidism which resulted in testicular temperature equal to core temperature. Moore [16], [17] found the tubular epithelium of the guinea pig highly disorganized after retention in the abdominal cavity for a period of 5 days, and completely disorganized in 7 days. He also [18] found complete degeneration of the ram's germinal epithelium 80 days after testicular cooling was prevented by enclosure of the scrotum in a loose fitting thermal insulating wool bag. Wangensteen [19] found considerable destruction of the dog's tubular epithelium after 5 days of cryptorchidism. Knaus [20] produced cryptorchidism in rabbits and found 100 per cent fertility 2 days later, 60 per cent at 3 days, 33 per cent at 4 days and 0 per cent at 5 days.

It appears that normal body core temperature is damaging to the testes of many species. Although species normal core temperatures differ, that of the rat is close to the human. It is also known that human cryptorchidism is incompatible with normal testicular function, even though a well defined time factor is not known for the species.

In the present study, tubular degeneration in the dog testis was seen as low as 37°C for a 1-hour exposure. MacLeod and Hotchkiss [21] found a marked decrease in sperm counts in six normal humans 40 to 50 days after a 30-minute period of testicular temperature of about 40.5°C, caused by diathermy and warm air. Bauer and Gutman [22] produced necrospermia in five human subjects by two to six 20-minute diathermy treatments to the testes. Temperature in this series was not reported. Williams [23] reports degeneration in a rat testis which had been exposed to S-band microwaves for a total of 5 minutes, reaching a maximum temperature of 38.2°C at the end of the exposure. Imig, Thompson and Hines [24] found damage in the rat testis following a 5-minute exposure to infrared radiation which produced a testicular temperature of 40°C. The same authors found damage to rat testes caused by a 5-minute exposure to S-band microwaves at as low a testicular temperature as 31°C. This is difficult to reconcile with the infrared results and the fact that 31°C is within or below the range of normal rat testicular temperatures.

It is apparent that data on threshold temperature sensitivity with time is meager at present. The minimum temperatures which are suggested from the above review are roughly 37°C for 5 days, 37°C for 1 hour and 38.2°C for 1 minute. Although the last, from Williams, was a 5-minute exposure, the temperature was increasing throughout, reaching the maximum figure at the end of exposure. This should be equivalent to a somewhat shorter exposure at that temperature, say, 1 minute. We have then, a suggestion of threshold temperature according to time of exposure. At exposures of less than 1 minute, the threshold would probably be higher. For exposures of more than 5 days, it would undoubtedly be reduced.

The approximate curve of microwave field intensity and time of exposure for the testis may be refined somewhat. Time constant data must be brought into the calculations. In the series of dog testes, time constants were found in the rather large range of from 110 to over 2000 sec. This represents principally the wide individual difference in scrotal structure and, to a lesser extent, possibly circulation. The time constants of the dog testes were plotted with respect to their maintenance field intensities at each of several integral temperatures. Figs. 17 and 18 show these plots for 37°C and 38°C. Since the short time constant and the low equilibrium field represent the more sensitive condition, the suggested line was drawn on that side of the field of points. Several points along these lines were substituted in formula (13) of the Appendix, and the resulting curves plotted as in Fig. 19, which is the 38°C condition. In Fig. 20, the curves for 37°, 38°, 39° and 40°C are presented with respect to time and field intensity combination which would produce the indicated temperatures as a maximum for any testis having constants falling within the field of experimental points. Each line represents a line through the minima of the solid curve families as in Fig. 19. The dashed line in this figure is a hypothetical curve using the minimum I' and the minimum $I'\tau$. It could be used in the interest of some simplification but is somewhat in error on the safe side in the central portion. Although tempting, a hypothetical combination of minimum I' and minimum τ would be greatly misleading at the shorter times. A set of curves, such as those in Fig. 20, together with information on threshold temperatures according to time of exposure, could be used in the estimation of testicular hazard.

Since heat development from microwave exposure in the testis is nonuniform with respect to volume, differential temperatures are produced. These differentials are small with respect to the over-all temperature rise for intensities of 100 mw/cm² and below, as used in this study. At much greater intensities, localized heating results in a zone having a very short time constant by reason of cooling to the surrounding testicular tissue. The same mechanism, however, is responsible for a high I' for this zone, and a sensitivity which is not much greater than that which had been based on the low intensity field data.

This point was checked experimentally by exposing

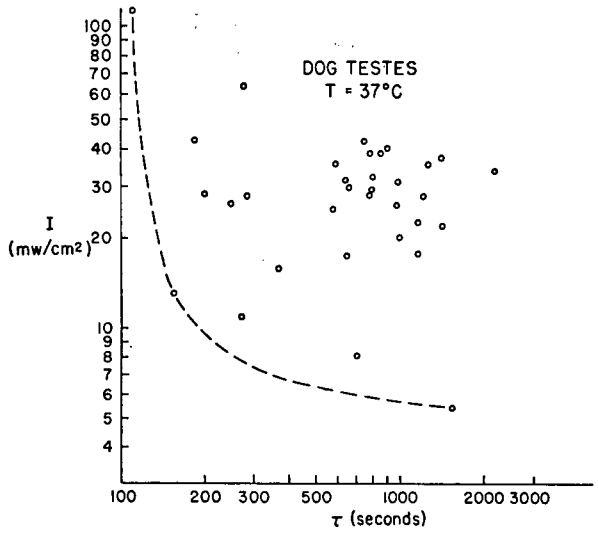

Fig. 17.

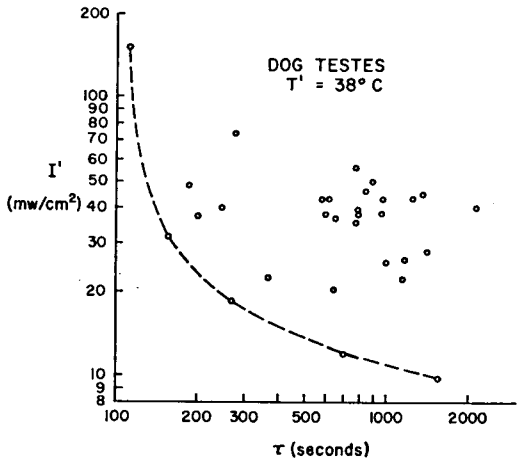

Fig. 18

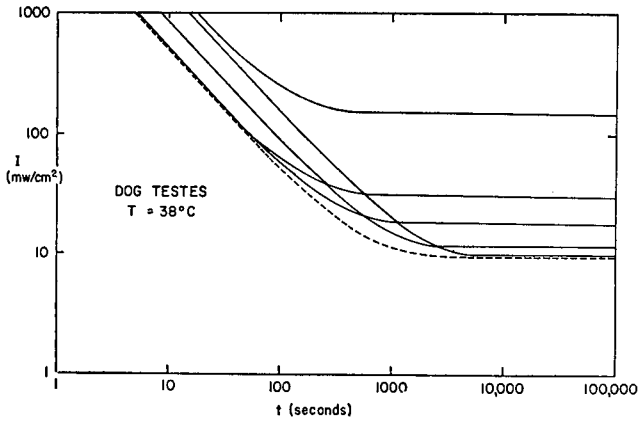

Fig. 19.

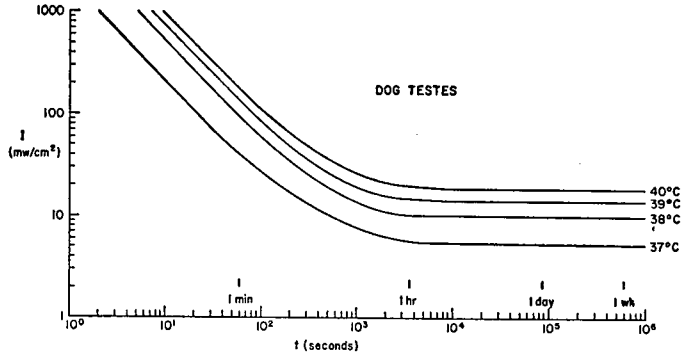

Fig. 20.

dog testes with the thermistor in the location of greatest heat production and time cycling the transmitter on a 3-sec cycle with a variable segment. This mechanism allowed reducing a very intense field of several watts per square centimeter, which produced significant differentials, to a much lower value in the order of less than 100 mw/cm², which produced negligible differentials. In this way the ratio between the field strengths could be determined accurately by pulse counting. Change of field strength by other means would have required measurement of actual field intensity, which is a procedure permitting of less accurate determination.

Essentially, one may conclude that as field strengths increase, testicular heating changes from a pattern of uniform temperature rise to that of temperature rise according to region of heat production. Since this latter does not vary with heating rate, it is the limiting factor in the production of differential temperatures. It would be expected then, that at the higher field intensities, corresponding to the shorter times, the curve would shift to a somewhat lower value, also having hyperbolic form.

An additional factor important in the evaluation of hazard is repetitive exposure. The irregular exposures cannot be treated in a general way, and would have to be evaluated on an individual basis. Regular exposures are to be seen in three main practical situations; those resulting from individual pulses of pulsed radar, which are repeated many times per second; those resulting from a scanning antenna, where repetition rate may be between 360 and $\frac{1}{2}$ per minute and those resulting from work schedules such as a 4-hour watch or an 8-hour shift. The principal reference in evaluating these repeated exposures is the time constant of the structure exposed. Pulsed radar pulse repetition rates are all much faster than any of the time constants demonstrated, as are the faster scanning rates, and time average field intensity is the proper value to be used in evaluation. This opinion is supported by Salisbury, Clark and Hines [8], and others. Repeated exposures occurring as a result of a daily shift or similar circumstance in which the repetition rate is several hours at least and is long with respect to tissue thermal time constants, should be treated as individual exposure incidents. The complex case occurs when the exposure repetition rate is of the same order of magnitude as the time constant of the structure in question. It would appear that the main example of this condition is with the slowly scanning radar antennas.

Evaluation of the hazard under conditions of a regularly repetitive exposure can be done by a reasonably straightforward mathematical analysis. Equations for

the general case can also be developed.

Although the criterion of hazard used in this study has been the least demonstrable damage, other factors should be considered in the over-all viewpoint. The minimal testicular damage is almost certainly completely reversible. Even considerably more severe testicular insult will probably be reversible, with the only finding being a temporary sterility. An even greater injury can result in permanent sterility, which result would evoke varying reaction.

In the case of the eye, a small, asymptomatic lens opacity would be of more concern than transient testicular damage. A disabling cataract would require only a moderately greater exposure, and would be considered a serious event.

From the whole body standpoint, minimum damage from generalized hyperthermia is difficult to evaluate. However, the large exposure resulting in death represents the ultimate effect.

Summary

Experimental animals were exposed to 10-cm microwave fields. From simultaneous temperature recordings of the animal, an evaluation was made of the heating effects. Cooling data enabled the formulation of curves of the time and field intensity required to achieve a given temperature. Of the three main sensitive structures, the whole body, the eye and the testis, the last was found to be an order of magnitude more sensitive than the other two. It was found that in the three structures, heating rate is essentially proportional to field intensity, and in the case of the eye and the testis, cooling rate was essentially proportional to the temperature elevation of the part. The whole body cooling rate is a complex function only partly dependent on the temperature elevation. Threshold damage temperatures were taken from the literature and, in the case of the testis, also from a histological evaluation which was part of this study. The heating, cooling and threshold temperature data were put into a somewhat general form, which may be useful in the estimation of hazards to humans.

The limitations of this study, such as those imposed by numbers of animals, restricted parameters and extrapolation from lower animals to humans, should be emphasized. Also, it should be stressed that this study attempts to provide but one link in the body of information which would be necessary to evaluate a hazard, and, therefore, of itself does not implicate or absolve any particular situation.

Acknowledgment

The authors express gratitude to Dr. R. G. Fellers and J. A. Kaiser of the Naval Research Laboratory for their frequent technical assistance on matters concerning the radar transmitter, and to L. T. Letchworth, Aviation Electronics Technician, First Class USN, for his capable operation of the transmitter and over-all assistance with the project.

APPENDIX

Some Mathematical Considerations

J. Z. HEARON

Consider a body of heat capacity C (cal/degree) which is being heated by an internal source S (cal/sec) and is cooling according to the law

$$\text{cal lost/sec} = \lambda a(T - T_0)$$

where λ (cal/sec cm^2 degree) is the loss per unit time per unit area for a unit temperature differential and a is the surface area of the body. Then

$$(\text{cal gained in } dt) = CdT = Sdt - \lambda a(T - T_0)dt$$

where dT is the temperature change in dt. Or, $T(t)$ is governed by

$$\frac{dT}{dt} = \frac{S}{C} - k(T - T_0) \qquad (1)$$

where $k(\text{sec}^{-1}) = \lambda a/C$. In the above it is assumed that S and T are *spatially uniform* and that T_0 is the external or environmental temperature. If spatial uniformity does not obtain, it can be shown that (1) still applies if I and S are replaced by their spatial or volume means and k has a different physical connotation (*i.e.*, $k \neq \lambda a/C$) but still represents a formal "cooling constant" in terms of the (spatial) average or mean temperature.[1,2]

In the situation at hand, T and S are not uniform but we wish to show that $T(t)$, measured at a fixed point in the body (*e.g.*, point of maximum temperature) does in

[1] N. Rashevsky, "Mathematical Biophysics," University of Chicago Press, Ill.; 1948.
[2] J. Z. Hearon, *Bull. Math. Biophys.*, vol. 15, p. 23–31; March, 1953.

fact obey an equation of type (1) wherein a specific assumption is made relating S/C to a known external energy field, and T_0 is taken to be the "normal initial temperature" (*i.e.*, the temperature in the absence of the external field).

In particular, assume

$$S/C = K'I \tag{2}$$

where I is the field intensity and K' is of the nature of a "pick-up" or "dissipation" coefficient, and independent of T and of the explicit time t. Then (1) is

$$\frac{dT}{dt} = K'I - k(T - T_0). \tag{3}$$

Denote the steady-state temperature by T_s and define the temperature rise at any t by

$$\Delta T(t) = T(t) - T_0 \tag{4}$$

and in the steady state

$$\Delta T_s = T_s - T_0. \tag{5}$$

Then (3) can be written

$$\frac{d\Delta T}{dt} = k(KI - \Delta T) \tag{6}$$

where $K = K'/k$.

The general integral of (6) is

$$\Delta T(t) = KI(1 - e^{-kt}) + \Delta T(0)e^{-kt}. \tag{7}$$

It is clear from (7), and otherwise obvious from (6) with $d\Delta T/dt = 0$, that

$$\Delta T_s = KI. \tag{8}$$

Thus (7) may be written as

$$\Delta T(t) = \Delta T_s(1 - e^{-kt}) + \Delta T(0)e^{-kt}. \tag{9}$$

The assumptions embodied in (2) can be checked through (8) which predicts the steady-state rise in temperature to be proportional to I. In particular the slope of the line (8) estimates K. The result (8) depends, of course, upon the assumed form $k(T - T_0)$ for the cooling law, but this can be validated separately and independently of assumption (2), as follows. If the body is heated, heating is stopped (*i.e.*, I made zero), and time is reckoned from the instant of cessation of heating, then from that instant on, $\Delta T(t)$ obeys [from (7) with $I = 0$]

$$\Delta T(t) = \Delta T(0)e^{-kt} \tag{10}$$

and under these conditions a semi-log plot of the temperature rise should be linear. The slope of this line estimates[3] $-k$. It is seen from (10) that beginning with any arbitrary initial temperature rise $\Delta T(0)$, the time required for the temperature rise to fall to $1/e$ of this initial value is $\tau = 1/k$. Or, beginning with an initial rise $\Delta T(0)$ of zero [*i.e.*, $T(0) = T_0$, see (4)] it follows from (9) that at time $\tau = 1/k$ the temperature rise achieves the fraction $1 - 1/e \cong 0.67$ of its final value.[4] It is convenient to deal with this characteristic time τ. We consider now *only* situations in which $\Delta T(0) = 0$. Then (9) is

$$\frac{\Delta T(t)}{\Delta T_s} = 1 - e^{-t/\tau} = \frac{\Delta T(t)}{KI}. \tag{11}$$

Consider a system being heated under field intensity I, its temperature rise being given by (11). Then for any t, and corresponding $\Delta T(t)$, there exists an intensity $I' \leq I$ which will produce a steady-state temperature rise equal to the observed temperature rise $\Delta T(t)$ at that time. It is clear from (7) that the inequality $I' \leq I$ is not valid unless $\Delta T(0) \leq KI$. But the agreement to consider $\Delta T(0) = 0$ entitles us to speak of the *reduced intensity* I' such that if the system is heated till time t under intensity I and at that time the intensity is instantaneously reduced to I', the temperature rise $\Delta T(t)$ obtained at that time will be maintained constantly and indefinitely. Plainly I' is a function of t and I but we do not display that fact in the notation. According to the argument leading to (8), I' is given by

$$KI' = \Delta T(t) \tag{12}$$

and (12) into (11) yields

$$\frac{I'}{I} = 1 - e^{-t/\tau} \tag{13}$$

or

$$\ln\left(1 - \frac{I'}{I}\right) = -t/\tau. \tag{14}$$

According to (11), if we prescribe a temperature rise, say $\Delta T(t) = A \leq KI$, then given A, there is, for each time t, an intensity I such that the temperature rise is precisely A at time t. These times and intensities are related by

$$A = KI(1 - e^{-t/\tau}) \tag{15}$$

for small t, *i.e.*, $t \ll \tau$,

$$A = \frac{K}{\tau} It = K'I \cdot t. \tag{16}$$

Thus over the range of sufficiently small t (and large I) the hyperbolic relation 16 holds. The slope of the initial linear portion of the log I vs log t plot is -1, the ordinate intercepts log (A/K').

[3] Also, k can be estimated in a slightly different fashion, see (14) and compare text.

[4] Stated otherwise, at time $\tau = 1/k$ the fractional displacement of the temperature rise from its steady-state value is $1/e$, *i.e.*,

$$\frac{\Delta T_s - \Delta T(t)}{\Delta T_s} = 1/e.$$

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ON *BIO-MEDICAL ENGINEERING*
Volume BME-11, Number 4, October, 1964
pp. 123-137
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