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Epidemiology

Standards

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Uses

Reactions

Sampling/Analytical Methods

Reported Ambient Levels

Measured Methods

Work Practices

Engineering Controls

Biological Monitoring

Methods of Analysis

Treatment

Transportation/Handling/Storage/Labelling

MR548

ORIGINAL CONTRIBUTIONS

A physical investigation of heat production in human tissues when exposed to microwaves

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Experimental investigations of temperature rises produced in parts of the human body during exposure to microwaves of 10 and 9·4 cm wavelength are described. Application of linear heat flow theory shows that the experimental skin temperature rise in the initial stages of a microwave exposure is consistent with a thermal conductivity for tissues of 0·005 cal cm^{-1} sec^{-1} °C^{-1}. With occlusion of the blood supply to the irradiated region the conductivity remains at this value until the pain threshold is reached. With no occlusion, increase in blood supply due to heating causes the effective conductivity to rise during exposure, but the theory becomes inapplicable as soon as heat flow is non-linear. Comparison is made of theoretical and experimental subcutaneous and muscle temperatures after microwave exposure and the differences explained. The influence of wavelength variation and air-cooling of the skin are discussed.

A preliminary report of investigations of the effects of microwaves on humans and animals has already been published.[1] This paper will be concerned mainly with the thermal analysis of some of the results reported previously and of some obtained more recently. The application of conduction theory has been found to provide information regarding the thermal conductivity of human tissues whilst exposed to microwaves, and to comparison between the experimental and theoretical temperature distribution at a depth.

A brief description follows of the experimental arrangements by which the results to be discussed were obtained.

OUTLINE OF THE EXPERIMENTAL ARRANGEMENT

Arrangement using a pulsed source of microwaves of 10 cm wavelength. Pulsed radiation from a type 277 Naval radar set was transmitted by rectangular wave-guide (7·62 × 2·54 cm) to the apparatus shown diagrammatically in Fig. 1. The part of the body to be

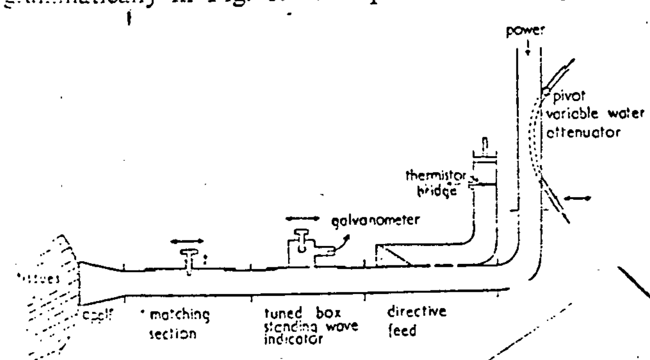

Fig. 1. Diagrammatic section of ...ngular waveguide apparatus used at 10 ...avelength

irradiated was placed in cor... with the aperture of the wave-guide applicator and ...ow power, a match was quickly achieved by adjusting the mismatch unit until the output from the directive feed was decreased to zero. The feed-through wattmeter (also acting as a standing wave indicator), previously calibrated against a water load, then enabled the water attenuator to be adjusted until the level of power required for the irradiation was obtained.

The free-space wavelength of the radiation was 10 cm, the pulse length 0·6 μsec, and repetition frequency 500 c/s. Average power, rather than that in the pulse, is the factor determining heat production and the results were related to this throughout. Two applicator sizes were available, 7·6 × 7·0 cm, and 3·8 × 2·5 cm, both rectangular. The smaller aperture was provided by a short length of wave-guide of this size filled with Perspex to allow progressive wave propagation. The field strength variation across the aperture was determined by the mode of propagation, H_{01}. There was thus a sine law variation of field strength across the longer axis, no variation with position occurring in the direction at right-angles.

Arrangement using a continuous wave source at 9·4 cm wavelength. Equipment was designed (in collaboration with T. J. Buchanan) for clinical applications, employing a continuous wave magnetron kindly lent by the General Electric Co. Ltd. Power from the source was fed by cable to either of the rectangular applicators described above or to a cylindrical H_{11} waveguide, the aperture of which provided, by means of interchangeable diaphragms, two applicator field sizes of 7 cm and 3·2 cm diameter respectively.

The power transmitted into tissues terminating the ...-guide applicators was a function of the magnetron c... ...t. Previous calibration with a water calorimeter th... ...nabled the power to be estimated from the mag... ...on current.

over

Thermometric arrangements. Temperatures were measured with thermocouples connected to a suitable galvanometer and previously calibrated. For the skin temperature measurement it was found possible to use a junction of fine copper and Constantan wires stretched across the aperture in contact with the skin and at right-angles to the electric field vector, the junction being at the centre of the field. No field pick-up effects were observed with powers several times higher than those used for tissue heating. The big advantage of this technique was that skin temperature variation could be recorded during the exposure.

Subcutaneous and muscle temperatures were measured with a steel hypodermic needle, at the point of which was a junction with an insulated copper wire running inside the needle. Measurements at various depths were made as quickly as possible after exposure. Since temperatures at each depth were measured at different times after exposure, corrections have been made to allow for differences in cooling at each depth.

Accuracy. The accuracy of power measurement was worst for low powers, where the limits of error were estimated to be $\pm 5\%$. These limits decreased progressively as the power increased. Skin temperature rises were thought to be quite accurate, to about $\pm 0{\cdot}1°$ C, but tissue temperature rises suffered wider error limits. This was due mainly to some uncertainty in the cooling corrections applied, but possible errors arising from heat conduction along the steel needle have also to be considered. The work of Mendelssohn and Rossiter[2] would appear to suggest that the latter are negligible. It is thought that tissue temperature rises are accurate to $\pm 0{\cdot}3°$ C.

DISTRIBUTION OF POWER IN THE MICROWAVE BEAMS

Dielectric constant measurements on human skin, fat, muscle and bone, reported elsewhere,[3] have enabled the absorption coefficients of these tissues for microwaves of various wavelengths to be evaluated. The power distribution in a plane perpendicular to the electric field

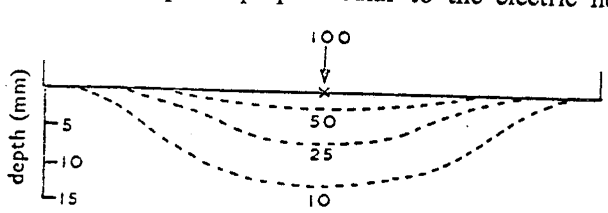

Fig. 2. Isopower curves in saline phantom

Principal plane perpendicular to electric field; $7{\cdot}6 \times 7{\cdot}0$ cm aperture; $\lambda = 10{\cdot}0$ cm.

and containing the central axis of the microwave beam was then measured experimentally by means of a probe moving in a saline solution. The salt concentration temperature of this were adjusted to have an a coefficient equal to that for human muscle a for wavelengths of 10 cm and 9·4 cm. To illustrate the results obtained, Fig. 2 shows isopower curves in such a phantom when microwaves of 10 cm wavelength from the $7{\cdot}6$ cm $\times$ $7{\cdot}0$ cm applicator were applied. The actual power distribution in the human arm or thigh would differ somewhat from that shown since wave propagation would be modified by the presence of the skin and subcutaneous fat layers, which have dielecric constants and absorption coefficients different from those of muscle.

The power distribution in the plane of the aperture and transverse to the beam axis is shown in Fig. 3 for

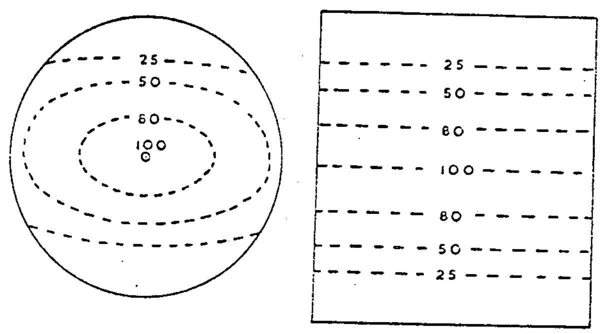

Fig. 3. Theoretical power distribution in plane of the apertures

7 cm diameter circle and $7{\cdot}6 \times 7{\cdot}0$ cm rectangle

the cases of rectangular and circular apertures. These distributions have been derived from the theoretical electric field patterns in the plane of the aperture. They can be taken as representing approximately the power distribution at the skin surface when tissues are irradiated.

SOME OF THE EXPERIMENTAL RESULTS ON HUMANS

Male volunteers were used, the inner forearm and anterior thigh being irradiated. Investigations of the variation of skin temperature with power and time were made, some representative results being shown in Figs. 4, 5 and 6. In all cases the temperatures shown are those at the central point of the exposed area. Differences between individuals were not unexpected but, in the main, these were small.

Investigations of the temperatures in the subcutaneous and muscle tissues along the central axis of a microwave beam were also carried out in collaboration with A. C. Boyle and others. A typical set of results for a male thigh are shown in Fig. 7 where the temperatures all relate to 30 sec after the termination of the exposure times shown against the curves.

DISCUSSION

The c itions under which the above experimental results wer tained approximate to those of a semi-infinite solid internal heat generation. The case of

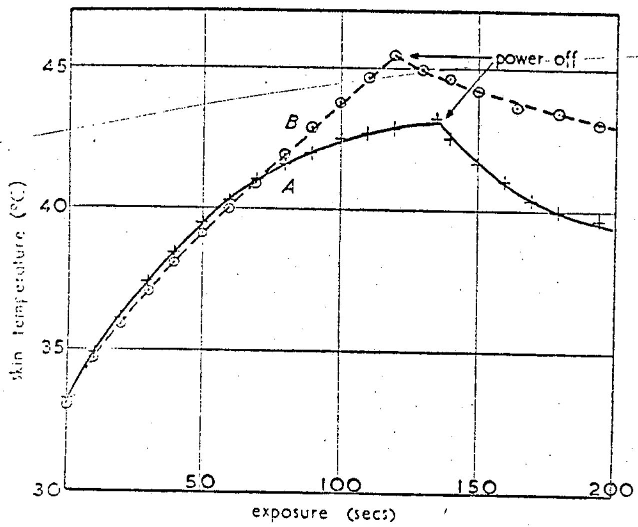

Fig. 4. Skin temperature *v.* exposure

Curve *A*—normal blood supply.
Curve *B*—with occlusion of blood supply.
Forearm; $7 \cdot 6 \times 7 \cdot 0$ cm rectangle; $\lambda = 10 \cdot 0$ cm; power = 17 W; room temperature = 20° C.

the semi-infinite solid in which the rate of heat production depends on depth according to $A_0 e^{-\alpha x}$, and where the surface at $x = 0$ is held at zero temperature, has been dealt with by Carslaw and Jaeger.(4) In the present case it can be assumed that heat flow into the irradiated tissues only need be considered. That into the terminating material of the microwave applicators (cork or Perspex) will be assumed negligible in comparison, since these materials have conductivities much lower than that of human tissues.

An extension of the case treated by Carslaw and Jaeger to cover the present condition where the temperature at $x = 0$ is allowed to rise is due to A. J. Vendrik (unpublished work). The relation derived, using the notation of Carslaw and Jaeger, is:—

$$v_x = a + bx + \left(2b + \frac{2A_0}{K}\right) \cdot \sqrt{(kt)} \cdot ierfc\left[\frac{x}{2\sqrt{(kt)}}\right]$$
$$+ \frac{A_0}{2\alpha^2 K} \exp(\alpha^2 kt - \alpha x) \cdot erfc\left[-\frac{x}{2\sqrt{(kt)}} + \alpha\sqrt{(kt)}\right]$$
$$+ \frac{A_0}{2\alpha^2 K} \exp(\alpha^2 kt + \alpha x) \cdot erfc\left[+\frac{x}{2\sqrt{(kt)}} + \alpha\sqrt{(kt)}\right]$$
$$- \frac{A_0}{\alpha^2 K} \exp(-\alpha x)$$

where

v_x = temperature at time t and at depth x.
a = initial temperature at $x = 0$.
b = temperature gradient.
A_0 = heat developed per unit time per [illegible]ne at $x = 0$.
α = energy absorption coefficient
K = thermal conductivity.
$k = K/$(density × specific he[illegible]

Use of this relation in conjunction with experimental results has enabled the thermal conductivity of the irradiated tissues to be calculated.

Skin temperatures during exposure to microwaves

Of the experimental results of skin temperature rises, those shown in Fig. 4 were obtained under conditions which approximate most closely to the semi-infinite solid. They also show the marked effect of occlusion of the blood supply.

To apply the theory to the experimental case it is necessary to relate the microwave power with A_0, to choose the correct value of α and to know the initial temperature gradient, b. It is also necessary to allow for the transverse power density variation across the irradiated area.

Taking the central block of tissues of cross-section, 4×7 cm, it was found experimentally that the average temperature of the skin after irradiation over this area was $0 \cdot 9$ of that measured at the central point. It was also found from the known power density variation that if W is the power in watts crossing the whole cross-section of the applicator, the average power density in the central section, 4×7 cm was $0 \cdot 030$ W. It can then be shown that the average value of A_0 for this case is given by:

$$A_0 = 0 \cdot 00723 W\alpha \text{ cal sec}^{-1} \text{ cm}^{-3}$$

The absorption of energy in the central block of tissues, 4×7 cm, can be shown, by analysis of the isopower curves of Fig. 2, to approximate closely to that for a plane-wave if a 10% increase in the plane-wave absorption coefficient is made. A theoretical study of plane-wave propagation in human tissues (to be described elsewhere) has shown that, in the present case of the forearm, the effective plane-wave absorption coefficient is not much lower than that for muscle, the influence of the thin skin and fat layers being small. The dielectric constant measurements already mentioned have shown that the value of this absorption coefficient for muscle at a wavelength of 10 cm is approximately $1 \cdot 5$. Hence this value for α was used in the thermal analysis since the two effects above tend to cancel each other.

The temperature gradient, b, was not measured in this case, but was taken as 2° C per cm, a figure appropriate to the prevailing room temperature. The specific heat and density of the tissues of the forearm were both assumed to be unity in their respective units.

It was then found that curve B (with occlusion) of Fig. 4 agreed well with a theoretical one calculated using the above data and a thermal conductivity, independent of exposure time, of $0 \cdot 005$ cal cm^{-1} sec^{-1} °C^{-1}. This [illegible]ure fits well into the range of values of conductivity ([illegible] to 10^{-2}) quoted in the literature for normal tiss[illegible] [illegible]nd shows that, with occlusion of the blood supp[illegible] [illegible]he heat production caused by microwave irradia[illegible] has little effect on the thermal conductivity.

Curve [illegible]f Fig. 4 was analysed similarly and showed that the effective thermal conductivity of the tissues rises to high values as the exposure proceeds. The temperature rise in the first 30 sec is consistent with $K = 0{\cdot}005$, but the temperature reached after 2 min can only be explained by assuming that the average conductivity operative over this period was increased to 0·015, the instantaneous value of K operative at this time being even higher. This increase can be related to the known enhancement of blood circulation and must be allowed for in theoretical calculations of tissue temperatures obtained when the human body is exposed to any thermogenic agent. The loss of heat from the irradiated region by means of transference by blood flow to non-irradiated regions becomes so large at longer exposures as to make worthless any comparison of experimental results with theoretical values based on the assumption of linear heat flow.

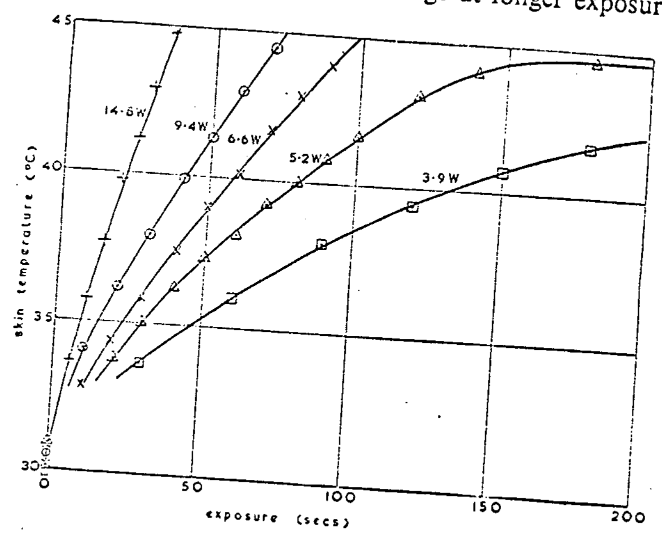

Fig. 5. Skin temperature *v.* exposure

Forearm; 3·8 × 2·5 cm aperture; $\lambda = 10{\cdot}0$ cm; room temperature = 19° C.

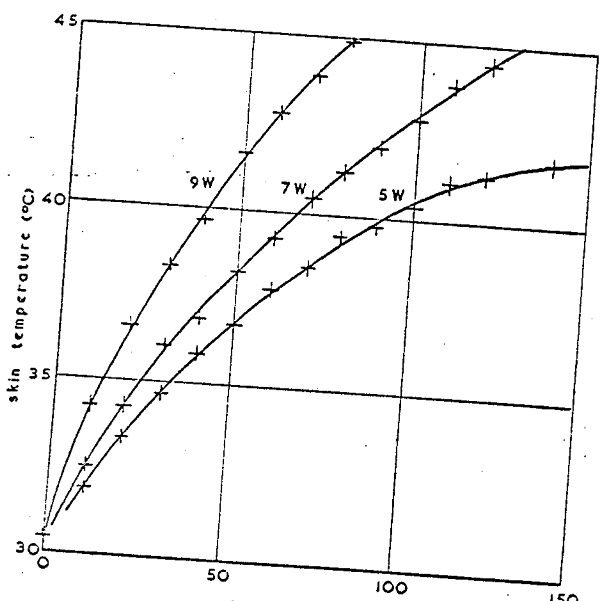

Fig. 6. Skin temperature *v.* exposure

Anterior thigh; 7 cm circular aperture; $\lambda = 9{\cdot}4$ room temperature = 17° C.

The results shown in Figs. 5 and 6 have been analysed in a similar manner. The thermal conductivities obtained from the analysis are of the same order as those above, but the analysis is less accurate owing to the smaller area involved in the one case, and to the greater transverse power density variation in the other.

Subcutaneous and muscle temperatures

It is of interest to compare experimental tissue temperatures after irradiation with temperatures calculated from Vendrik's relation. Fig. 8 provides such a comparison for the irradiation conditions stated. To obtain the theoretical curves the values of the effective thermal conductivity derived in the preceding section have been used in the calculations. The experimental curves in this case are based on the mean results obtained using three individuals, the temperatures being corrected to refer to the time the exposures terminated.

Reasonable agreement is obtained between experiment and theory for these relatively short exposure times. Attempts to obtain agreement in the case of longer exposure times fail, however, even assuming K to increase considerably. Thus, it can be concluded that the flow of heat in irradiated tissues is approximately linear during the initial stages of exposure, but is no longer so when the exposure is prolonged. This is due, presumably, to a progressive increase in vasodilation and lateral heat transference out of the irradiated zone during exposure.

Interesting features of the experimental curves of temperature as a function of depth are the trough and peak in the curves, not apparent in the theoretical ones. These can be correlated with the existence of a layer of fatty tissue interposed between skin and muscle tissues. Adipose tissue has a dielectric constant and loss much lower than those of skin and muscle. It will be shown in another paper that the combined effect of the lower energy absorption in the fatty tissue layer and the multiple reflexion of radiation at the tissue interfaces is to modify the shape of the temperature-depth curve from that of the theoretical one in homogeneous muscle (Fig. 8) to that of the experimental curves shown in Figs. 7 and 8. The effect depends on the thickness of the fat layer. The results presented here refer to thighs where this thickness is approximately 6 mm.

Influence of wavelength on temperature rises of skin and subcutaneous tissues

The effect of a change in wavelength (and hence ...p. ...coefficient) on temperature rise can be calculated. It ... be shown readily that the transmitted intensity of ra... ...n required to produce any given skin temperature ris... ...er prolonged exposure is inversely proportional to ... absorption coefficient. Thus, the

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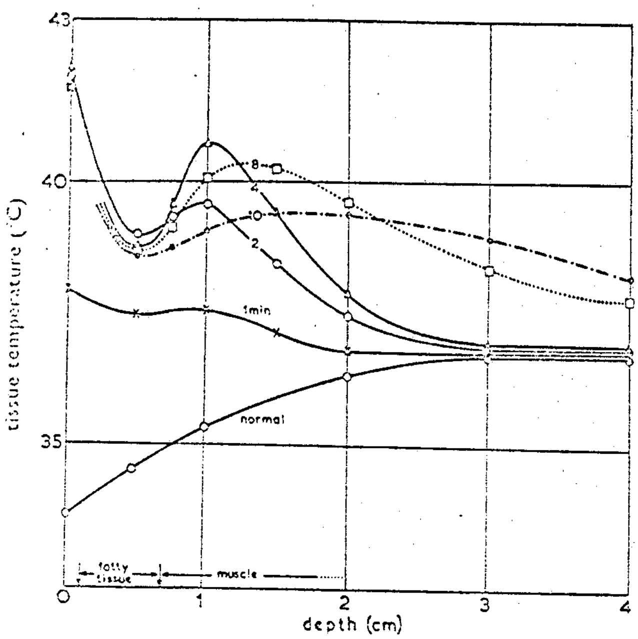

Fig. 7. Tissue temperature *v.* depth 30 sec after exposure times shown

Anterior thigh; central axis of field $3 \cdot 8 = 2 \cdot 5$ cm; $\lambda = 10 \cdot 0$ cm; power = 3 W; room temperature = 25° C.

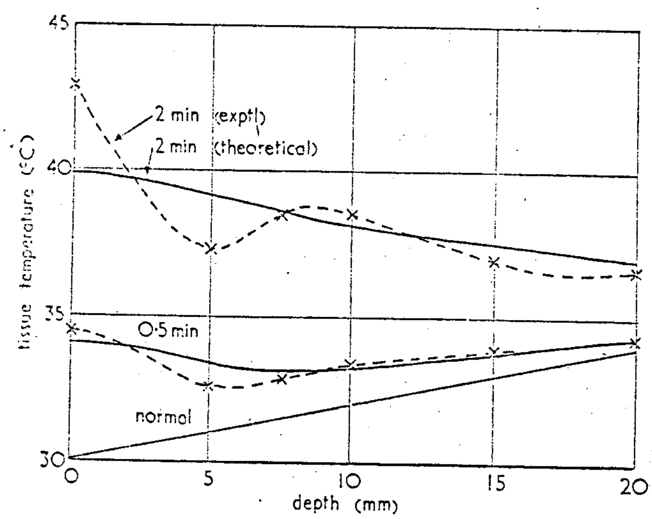

Fig. 8. Tissue temperature *v.* depth

Full lines: theoretical for plane wave in muscle; $\lambda = 10 \cdot 0$ cm; $0 \cdot 42$ W cm−2.
Broken lines: experimental for central axis of beam from aperture $3 \cdot 8 \times 2 \cdot 5$ cm in tissues of anterior thigh; $\lambda = 10 \cdot 0$ cm; $2 \cdot 5$ W.

transmitted intensity of infra-red radiation (from a therapeutic heat lamp) and of $1 \cdot 25$ cm microwaves ($\alpha = 15$ in both cases), which can be tolerat... the human body without pain, is 1/10th ... d intensity of 10 cm microwaves (α - ...

Use of the theoretical relati... sed on linear heat flow) to determine the effect ... change of wavelength on temperature variation w... depth in irradiated tissues must be confined to cas... here the exposure time is short enough for the li... heat flow condition to be satisfied approximately. Fig. 9 shows the theoretical temperature distribution in superficial skin and muscle tissues (negligibly thin fatty layer) after a 2 min exposure to microwaves of different wavelengths. Although the absorption coefficient decreases from 15 at $1 \cdot 25$ cm wavelength to $1 \cdot 5$ at 10 cm wavelength, the relatively high thermal conductivity has the effect of decreasing considerably the differences in temperature gradient which might be expected from such a difference in absorption coefficient. For wavelengths longer than 10 cm the absorption coefficient falls very slowly with increasing wavelength, and the temperature variation with depth will differ little from that shown for 10 cm wavelength.

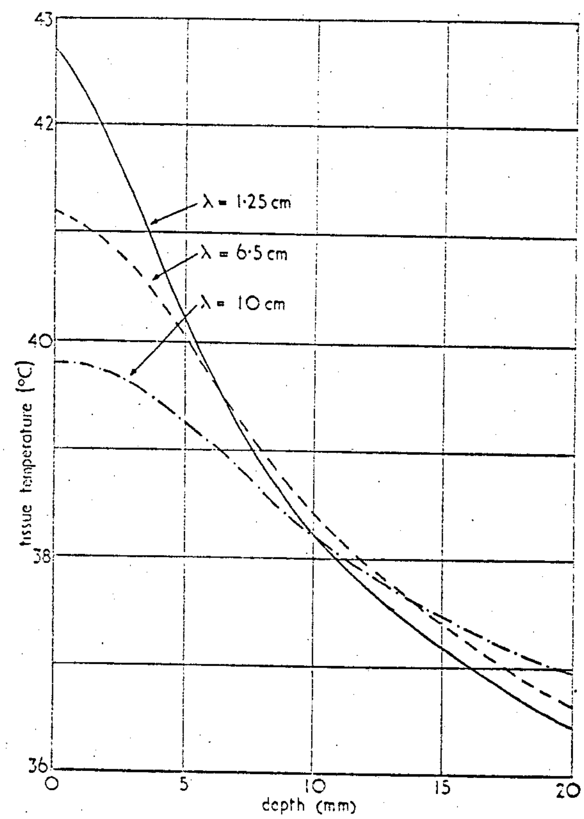

Fig. 9. Theoretical tissue temperatures for plane wave propagation in muscle after 2 min exposure at different wavelengths

Initial skin temperature = 30° C; initial temperature gradient = 2° C cm−1; thermal conductivity = $0 \cdot 015$ cal cm−1 sec−1 °C−1; $0 \cdot 42$ W cm−2.

Since the reflexion coefficients of tissue interfaces (skin-fatty tissue, fat-muscle, muscle-bone) are relatively constant in the microwave region,[3] the magnitude of the effect of the presence of fatty tissue and bone in modifying the temperature variation with depth should be approximately independent of wavelength.

The influence of heat losses to the region $x < 0$

...re tissues are exposed to radiation under conditi... such that heat is lost to the region $x < 0$ (by radiation, convection and vaporization) the preceding theory and arguments may no longer hold. Such conditions obtain in therapeutic practice where an air space intervenes between the exposed region of the body and the microwave applicator.

If the loss of heat at the surface to the region $x < 0$ is at a high rate, the surface temperature does not rise and the theoretical variation of temperature rise with depth would be of the type shown in Fig. 10. However, with room conditions normally encountered the loss of heat to the region $x < 0$ is relatively small, the skin temperature rises, and the temperature gradient is considerably reduced. Another factor contributing to the reduction of the temperature gradient is vasodilatation. In experiments on animals under air-cooling conditions (carried out in collaboration with A. C. Boyle

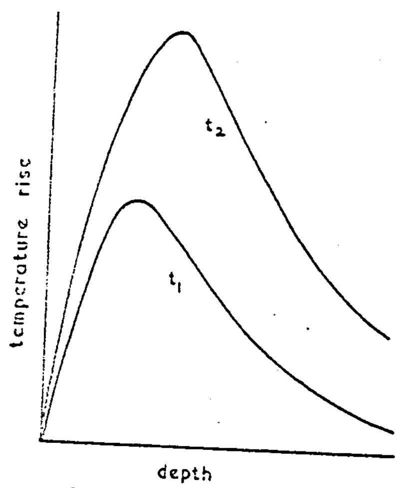

Fig. 10. Form of the theoretical temperature rise variation with depth in homogeneous tissues exposed under conditions where the surface temperature is held constant ($t_1 < t_2$)

and D. L. Wolfe) no evidence has yet been obtained of the existence, during exposure, of temperatures at depths below the skin in excess of those of the skin, in anatomical regions well supplied with blood.

A positive temperature gradient in tissues exposed in the presence of air-cooling can be found experimentally a short time after the termination of exposure, but when allowance is made for the rate of cooling at the surface being greater than at a depth during temperature measurements, it is found that the corrected gradient is approximately zero. This suggests that, in practice, the loss of heat to the region $x < 0$ under normal air conditions is not sufficiently great to cause any large qualitative change from the results found when the exposed tissues are in contact with a poor thermal conductor.

In other experiments with gelatine phantoms, exposed under air cooling conditions to 10 cm microwaves, the temperature gradient (corrected for cooling during temperature measurements after exposure) was fo... be positive only when the surface at $x = 0$ was subjected to strong air currents.

Clark[5] has given preliminary details of results obtained when the eye and testicle of a rabbit were exposed to microwaves, presumably under air cooling conditions. Evidence is obtained of a positive temperature gradient in the eye and it is suggested that the absence of blood circulation makes this possible. The experiments with gelatine mentioned above would indicate that Clark's result was obtained under strong air-cooling conditions.

CONCLUSIONS

Human tissues exposed to microwaves undergo temperature rises which, in the initial stages of the exposure, are in approximate agreement with those calculated on the assumption of linear heat flow if it is also assumed that the effective thermal conductivity of tissues rises from a value of $0 \cdot 005$ cal cm^{-1} sec^{-1} °C^{-1} to much higher values as the exposure proceeds.

However, the divergence of the experimental case from the theoretical one of the semi-infinite solid with linear heat flow becomes too great for comparison to be made as soon as capillary dilatation due to heating becomes significant.

It can be concluded that, when the microwave exposure is made with the irradiated region in contact with a poor thermal conductor, the skin undergoes the highest temperature rise. However, it is possible that, if exposure is made in the presence of strong air cooling, the temperature rise at depths below the surface may exceed that of the skin. This is likely to occur only in anatomical regions devoid of blood circulation.

ACKNOWLEDGMENTS

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