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Animal Toxicology

Non-occupational Human Exposure

Occupational Exposure

Epidemiology

Standards

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Uses

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Sampling/Analytical Methods

Reported Ambient Levels

Measured Methods

Work Practices

Engineering Controls

Biological Monitoring

Methods of Analysis

Treatment

Transportation/Handling/Storage/Labelling

THE EFFECTS OF MICRO-WAVES

A PRELIMINARY INVESTIGATION

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UP TO the present time, reports in the literature concerning the biological and other effects of radio-waves below 30 centimetres in wave-length are not extensive. The use of radar in World War II gave rise to speculation on the possible ill effects in operators of micro-waves, but Daily (1943) and Follis (1946), using both Service personnel and laboratory animals, found no evidence to support this, and Lidman and Cohen (1945) could find no evidence of activity of these waves on haemopoietic tissues.

Nature and action of micro-waves

Krusen (with various colleagues) showed that micro-waves of 12 centimetres wave-length were capable of heating living tissues, and later studied their effect on the peripheral circulation of dogs (Krusen and his colleagues, 1947; Leden and her colleagues, 1947; Wakim and his colleagues, 1949). Osborne and Frederick (1948), again using dogs, reported on the effect of 12-centimetre waves on the thighs, eyes and frontal sinuses of these animals, and Rae and his colleagues (1949) carried out a comparative study of micro-waves and short-wave diathermy.

Much of the work which has been carried out so far on the heating effect in living tissues has depended upon the use of hemispherical or rectangular directors, placed at a distance of 2·5—5 centimetres from the surface of the body. Because micro-waves behave in many respects like light rays, and can be refracted, reflected and diffracted, this method has necessitated the use of relatively high-power outputs (30—100 watts), for a large proportion of the waves are reflected from the surface of the tissue under investigation. Under these conditions, owing to variable factors, assessment of radiation absorption and accurate measurement of dosage are a matter of some difficulty.

This difficulty in measuring dosage has always been a disadvantage in short-wave therapy, in which the sensation of the patient must be used as a guide to the amount of heating of the tissues. Thermal sensation does not appear to be so marked during micro-wave irradiation as with other forms of heating, so that accurate mensuration of dosage becomes even more essential if this form of therapy is to be accepted into general usage.

During the past year we have been investigating the use of contact applicators in the irradiation of human and animal tissues with micro-waves of 10 centimetres' wave-length. Using this method, we have been able to produce similar rises in surface and subcutaneous temperature as have other workers, but by the use of lower power outputs. The apparatus has been so designed that no energy is wasted by reflection from the tissues, and this facilitates the measurement of the actual energy passing from the applicator into the body.

Technique of experiments

(1) *Source of radiation and transmission system*

The initial experiments have been carried out by the use of a typical 10-centimetre radar set, which delivers short pulses of high-frequency energy from a cavity magnetron, the duration of each pulse being 0·6 microseconds, and the pulse-repetition frequency 500 cycles per second. The average power available is variable up to about 100 watts, but power levels much lower than this have been found to be sufficient. The peak power in the pulse is approximately 3,300 times the average power.

The transmitter is housed in a trailer outside the laboratory, and the power is fed into the room along a rectangular waveguide, the internal cross-sectional dimensions of which are 1 × 3 inches. Inside the laboratory the waveguide run includes a water attenuator, a standing wave detector (which also acts as power monitor), and a matching unit. The waveguide run then terminates in the applicator. A photograph of the waveguide apparatus is shown in Fig. 1.

(2) *Function of the waveguide components*

Water attenuator (*A in Fig.* 1).—This is necessary for two reasons. First, the magnetron is apt to be unstable when large reflections occur in the output waveguide, and the presence of a fairly large attenuation allows alterations to be made at the termination without upsetting the frequency and output power of the magnetron. Secondly, the power output from the magnetron must be controlled and reduced to any desired level. This can be done by variation of the pulsed voltage applied to the magnetron, but this method is not so convenient as a control situated within easy reach of

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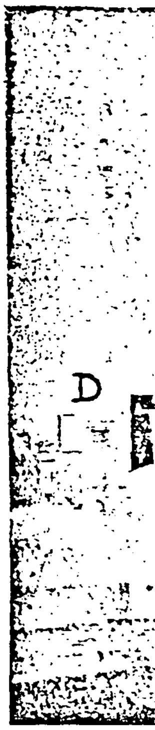

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the operator, such as can be provided by a water-filled glass tube, the insertion of which into the waveguide is controlled by a simple lever arrangement. A constant flow of water is required in this device, because rapid heating of the water occurs, due to the large absorption of energy at wave-lengths in the micro-wave region.

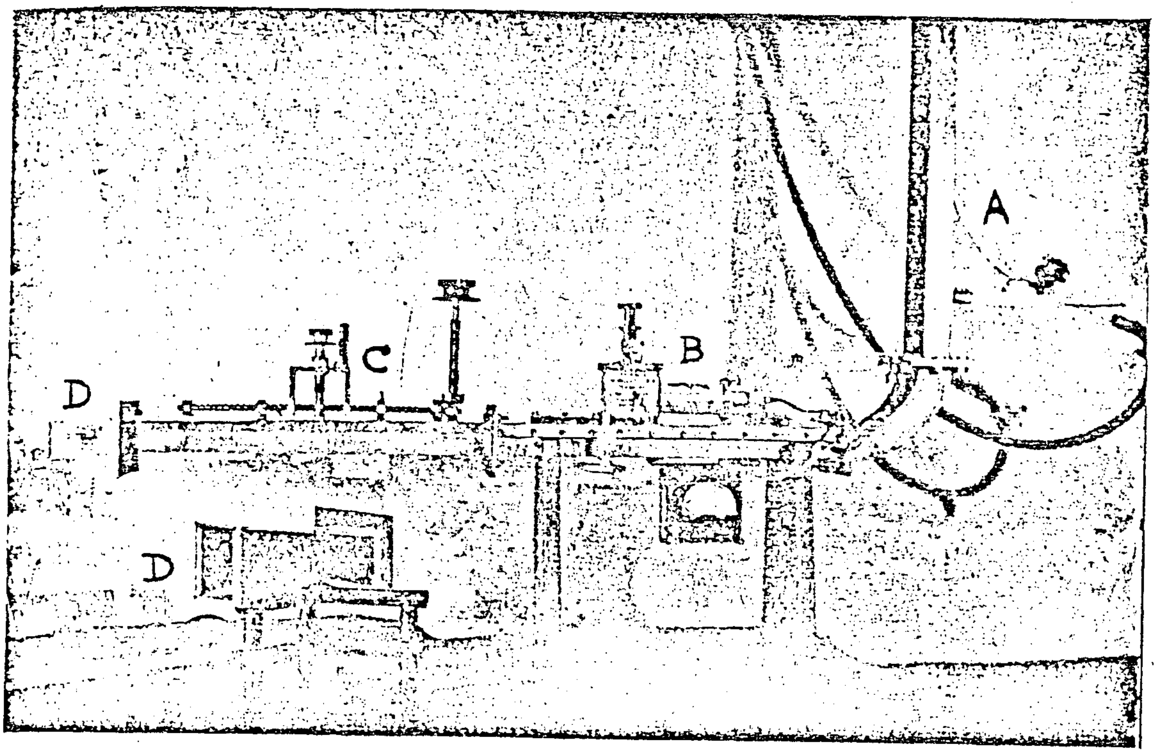

Fig. 1. *The wave-guide apparatus. A. = Water attenuator. B. = Standing wave detector. C. = Matching unit. D. = Applicators.*

Standing wave detector (*B in Fig.* 1).—This apparatus detects and measures the amount of energy reflected from the waveguide termination. A probe, moving along a narrow longitudinal slot in the broad face of the waveguide, feeds a small portion of the power into a thermocouple, and the variations of the thermocouple current, as the probe moves through the standing-wave pattern, give a measure of the standing-wave ratio in the waveguide. By calibration against a water load (using a calorimeter), the device can also be used as a power monitor and, with care, can be made to measure the power passing down the waveguide with an accuracy of about 5 per cent.

Matching unit (*C in Fig.* 1).—It is difficult to design a simple termination which does not reflect some of the radiation when in contact with living tissues. The termination is said to be mismatched when reflection of power occurs, and matched when all the incident power is absorbed by the tissues. In order to facilitate the measurement of power and to avoid trouble due to large standing waves in the guide, it is necessary to achieve an approximate match.

The applicators which we have used are not ideal in this respect, for they give rise to a residual reflection, which is still large enough to be troublesome. It is therefore necessary to make use of a matching unit which cancels this reflection, so that almost all the power passing down the waveguide from the water attenuator is absorbed in the tissues. When different applicators are used, or when different parts of the body are being irradiated, the magnitude of the reflection varies, and the matching unit usually requires a small adjustment in each case. The unit itself consists essentially of a thick metal post, which moves in a longitudinal slot in the guide, and is so arranged that both the depth of the insertion and the position along the guide can be varied rapidly.

Applicators (*D in Fig.* 1).—The applicator is simply a convenient termination for applying micro-wave energy to the required area of the body with the minimum of reflection. The better the match of this termination, the easier it is to adjust the matching unit so as to give perfect matching conditions.

Two applicators have been designed, and both can be rigidly attached, in turn, to the end of the matching unit; alternatively, they can be separated from the latter by a length of flexible circular waveguide. For the purpose of the investigations described below, the rigid attachment has been used.

The smaller applicator consists of a length of rectangular waveguide with a cross-section of 1·5 × 1 inch, providing a field of the same dimensions. This waveguide is filled with Perspex, and the length is chosen to give the minimum of reflection when the applicator is in contact with tissues. The main purpose of this applicator was to provide a small field for the irradiation of rats, but it has also been used on the human body.

The larger applicator has an aperture of 2·75 × 2·25 inches, and is tapered down to 1 × 3 inches, the cross-section of the standard waveguide. Tapering cuts down reflection, which would otherwise occur at such a change in cross-section.

Both applicators have Perspex covers, providing smooth surfaces, so that the blood-flow in the underlying skin is not impeded; in addition, the cover prevents sparking between the end of the metal guide and the skin.

(3) *Experimental procedure for irradiation*

Before exposure, the applicator is applied to a part of the body similar to that to be irradiated, and the matching unit is adjusted for optimal matching conditions. This is usually done at a fairly low power level, the water attenuator next being adjusted to give the power level required for the experiment.

The part of the body to be exposed is then placed in position for a measured time, rapid small adjustments being made to the matching unit if required, also to the attenuator at the commencement of exposure.

This method of passing the energy into the tissues enables the actual amount of energy absorbed to be measured. We consider this to be an advantage compared with methods already described, for the reasons mentioned in the introduction to this paper.

(4) *Thermometry*

Skin temperatures have been measured with a thermistor bridge circuit. The thermistor is of the bead type, the bead being located at the tip of a short length of glass tubing.

For the measurement of both subcutaneous and deeper tissue temperatures a thermocouple has been used, in the form of a steel hypodermic needle. A Constantan wire runs down the inside of the needle, terminating in a junction with the steel at the point of the needle.

The thermistor is thought to give skin temperatures to an accuracy of approximately 0·3°F., but tissue-temperature measurements, when the thermocouple is used, are subject to errors greater than this. Heat conduction along the needle is probably not sufficient, in comparison with that of tissues, to disturb appreciably the temperatures existing in the tissues. The accuracy of measurement of these temperatures, however, depends upon various factors, the effects of which are difficult to assess. We believe the temperatures to be accurate to approximately 1° Fahrenheit.

General observations

Sensation.—One of our earliest observations in this series of experiments was that the pressure of the applicator on the skin surface materially altered the sensation of heat felt. As might be expected, firm pressure, with consequent devascularization of underlying tissue, would cause less rapid dissipation of heat from the irradiated area than when light contact was maintained. In order to minimize this effect, a uniformly light and even contact was aimed at during all irradiations.

A second factor which appeared to alter the heating sensation was the formation of perspiration between the applicator and the skin. A similar effect could be obtained by moistening the skin with normal saline solution before irradiation. During hot weather, and with relatively high power levels, this factor was found to cause higher temperature readings than would otherwise be expected. This difficulty was overcome by the interposition of a thin towel between the applicator and the skin, as is often the practice with other forms of heat treatment.

With the smaller applicator a comfortable sensation of warmth was experienced during irradiation with powers of about 3 watts, though, with higher powers, heat sensation was not so marked as might have been expected from experience with other forms of heating. The sensation of warmth was constantly noted to build up to a maximum, after a time dependent upon field area and power level, and this observation is borne out by the temperature curves obtained (Figs. 2 and 3).

Erythema.—Redness of the skin was noted over the area of the field, and this was not less than would have been expected with other forms of heating to comparable temperatures. Areas of skin which were repeatedly used for irradiation showed no evidence of pigmentation or other change. On one occasion, a skin temperature of 111·5°F. was recorded, but there was neither subsequent blistering nor evidence of subcutaneous burn.

Methods of temperature measurement

The applicators used are described above. The area of the skin to be irradiated was marked off, and a light even pressure was maintained during exposure. For skin-temperature readings, the point of the thermistor was applied to the centre point of the field, and readings were completed within a period of 30 seconds.

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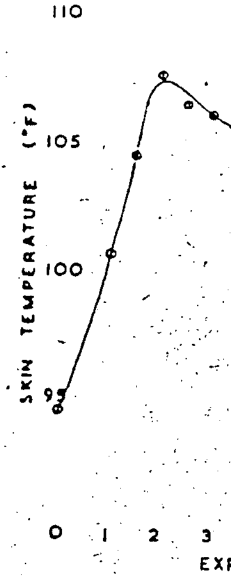

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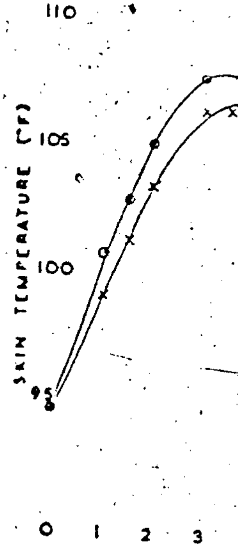

Fig. 3. Skin temperatu
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The small applicator was used for all subcutaneous work, so that temperature rises might be recorded accurately in the centre of the field. A point 9 inches above the upper border of the patella, on the front of the thigh, was used for all these readings. The skin of this area and the surface of the applicator were sterilized before exposure, and the needle thermocouple was kept in spirit, warmed in a water-bath to approximately 100°F. Immediately irradiation ceased, the needle was plunged to its maximal depth into the centre point of the field. Readings were then taken at 0·5-centimetre intervals during withdrawal of the needle. All readings were completed within 1 minute of cessation of exposure.

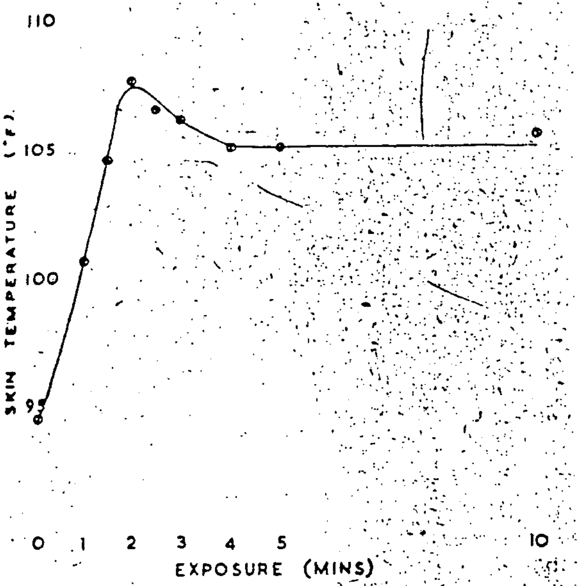

Fig. 2. Skin temperature v. exposure time. Field area = 1·5 × 1 inch. Power = 3 watts.

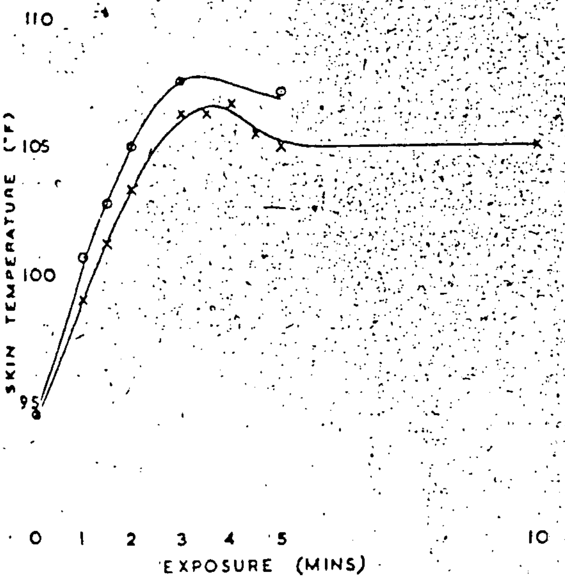

Fig. 3. Skin temperature v. exposure time. Field area = 2·25 × 2·25 inches. (X = 10 watts, ⊙ = 13 watts)

Results of measurements

These are recorded in graphic form in Figs. 2—5. Fig. 2 shows the skin-temperature rise against exposure time at a power output of 3 watts. This power level was found to be most satisfactory with the smaller applicator, giving a comfortable sensation of warmth throughout the irradiation. Outputs of 4·5 watts and above were found to be intolerable, owing to intense heating of the skin.

The curve in Fig. 2 shows a sharp rise at first, reaching a peak at 2 minutes, after which the temperature settles at a steady, but somewhat lower, level.

Fig. 3 shows similar curves with the use of the larger applicator. With this applicator, the optimal power level was between 10 and 15 watts. At 20 watts, irradiation had to be stopped after about 2 minutes, owing to intense heating.

Temperature distribution across the field was measured in two directions by taking readings with the thermistor at 0·5-centimetre intervals. The results are shown in Fig. 4. There is a rapid falling away of effect towards the periphery of the field.

Fig. 5 shows temperature curves for subcutaneous and deeper tissues plotted from measurements made after 1, 2, 4, 8 and 10 minutes' irradiation. The temperatures have had small corrections for cooling applied whenever necessary, so that all temperatures

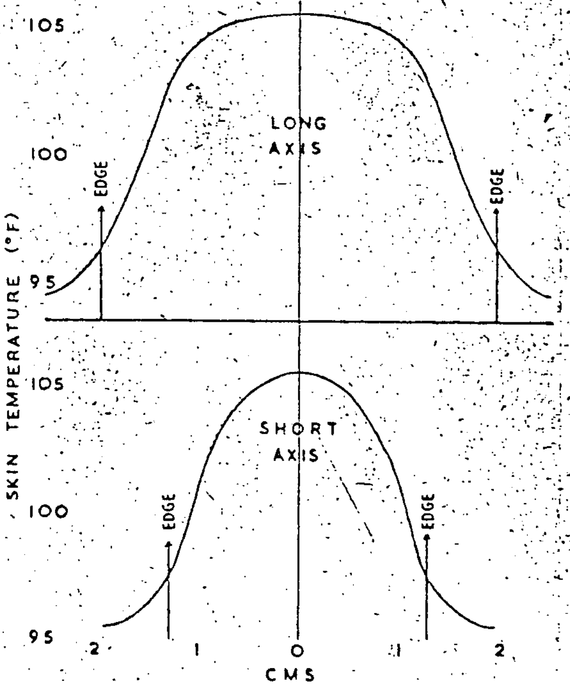

Fig. 4. Variation of skin temperature across the field. Field area = 1·5 × 1 inch. Power = 7 watts. Exposure time = 45 seconds.

(including those of the skin taken with the thermistor) refer to 30 seconds after the termination of exposure.

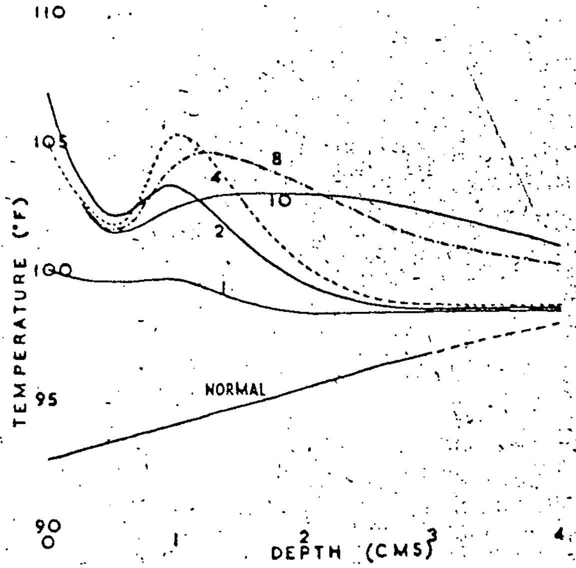

Fig. 5. Temperature v. *depth curves for exposure times from* 1 *to* 10 *seconds. Human thigh : field area* = 1·5 × 1 *inch ; power* = 3 *watts.*

Experiments on animals

Effects of overdosage.—The local and general effects of overdosage were studied in the laboratory animal. Under general anaesthesia, the skin of a female albino rat was plucked clean of hair over the outer aspect of the thigh, and this area was then subjected to a deliberate overdosage with microwaves, at a power level of 8 watts for 5 minutes. During irradiation the thigh gradually extended and, at the conclusion of the experiment, the thigh, leg, foot and toes of the animal were rigidly extended, with marked oedema at the site of irradiation and a greyish discoloration of the underlying tissue.

Post mortem, no general effects could be found. Locally, however, the skin, subcutaneous tissue and superficial thigh muscles showed coagulation necrosis (Fig. 6). The femur and deeper muscles were unaffected. From this single observation it would appear to be likely that the effects of overdosage are only local.

Effect of metallic foreign body in the field.—Under general anaesthesia, a metal disc, 1 centimetre in diameter, made of tin alloy, was inserted into the muscles of each of the thighs of a rabbit, at a depth of 1·5 centimetres.

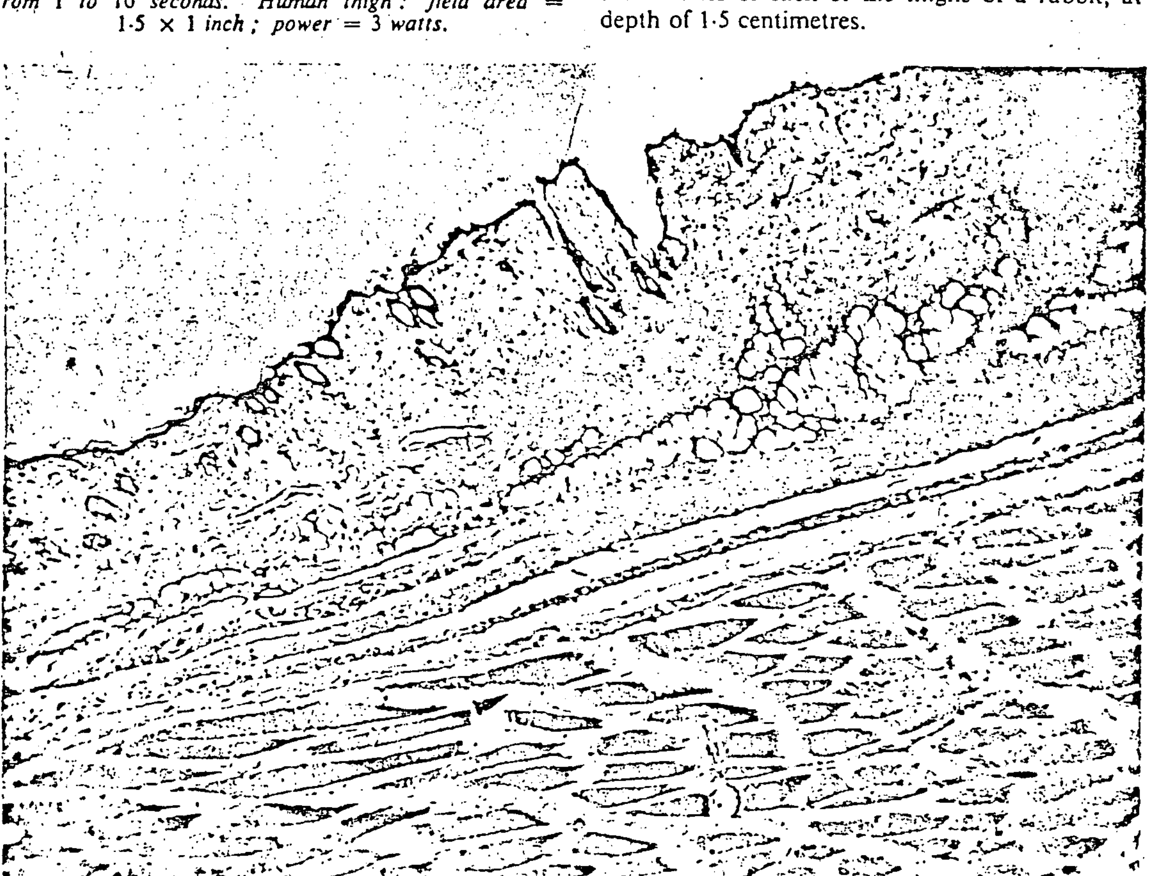

Fig. 6. Section of skin and muscles of rat's thigh, at edge of irradiated area. Normal skin on left. On right there is oedema and coagulation necrosis of skin and underlying muscles.

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After a lapse of 3 weeks, to allow foreign-body reaction to take place, one thigh of the animal was irradiated with micro-waves over the site of the metal disc, at an output of 3 watts for 15 minutes. At the conclusion of irradiation the skin temperature (measured with the thermistor) was 107·1°F., and the needle thermocouple inserted down to the metal plate read 108° Fahrenheit.

Ten days later the animal was killed, and the two thighs were examined. Microscopically, the control thigh showed a foreign-body reaction around the metal plate. In addition to this, the irradiated thigh showed evidence of coagulation necrosis of the adjacent muscles.

Discussion

The production of heat in tissues by micro-wave irradiation is mainly due to the dipolar nature of the water molecules present. Whereas in short-wave therapy ionic conductivity is the sole cause of heat production, this plays but a minor role in the case of irradiation by micro-waves of a free-space wavelength of 10 centimetres. In blood, it is estimated that roughly 80 per cent of the heat is produced by dipolar action, and the remainder by ionic conductivity.

The effective penetration of the radiation in pure water is about 2·5 centimetres. This is the depth at which energy production is 10 per cent of that of the surface. In living tissue no accurate estimate can be made, owing to non-homogeneity, but it is unlikely that the penetration would exceed this figure appreciably.

Because the absorption of the radiation will depend to a large extent upon the water content of the various tissues, it can be expected that bone and fat, with a lower water content than muscle or other vascular tissue, would absorb less than do these structures. The results reported by England and Sharples (1949) bear this out. These factors must be borne in mind when discussing experimental results.

Skin temperatures

The shape of our skin-temperature curves is similar to that of the curves obtained by other workers. The stabilization of temperature after an initial rise is probably due to adjustment of the local circulation, with vasodilatation, and of the eventual equilibrium of heat loss and heat gain. The time taken for equilibrium to occur would depend upon the area irradiated.

The non-uniform heating across the area is due in part to the sinusoidal variation of the electric field across one dimension of the aperture of the applicator, but some falling off of effect at the edges of the field would be expected on physiological grounds.

The most interesting feature of the results on human tissue is the shape of the curves showing temperature variation with depth. In the first centimetre below the skin we have both a negative and a positive temperature gradient. The initial fall of temperature may be due, we believe, to the presence of a fat layer a few millimetres below the skin, causing energy absorption to be lower at this level than at greater depths. De Sequin, Castelain and Pelletier (1948) have observed a similar initial fall in temperature with depth in experiments on dead tissues, when they used radiation of a wavelength of 21 centimetres.

Relation between time and temperature

There are other noticeable features.

(1) The temperature–time relationship varies according to the depth in the tissues at which the relationship is considered. For any given depth less than 2 centimetres, an examination of Fig. 5 shows that the temperature rises at first, as would be expected, but then shows a decrease with time.

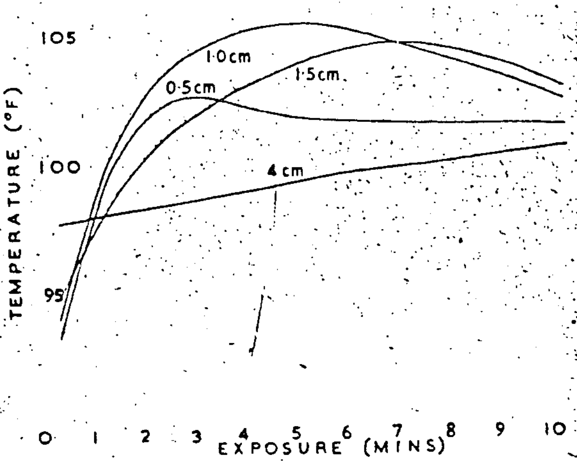

Fig. 7. Temperature v. exposure-time curves obtained from Fig. 5.

It can be seen that the time taken to reach the maximum of temperature at any given depth increases as the depth increases. At depths greater than 2 centimetres the curves show that the temperature is still increasing even after 10 minutes' irradiation. Fig. 7, obtained by interpolation on the curves of Fig. 5, shows this graphically.

(2) The curves become flatter, and the peaks slightly smaller, after the longer periods of irradiation.

This peaking of the temperature with time has already been noticed with skin temperatures, and the same explanation probably holds in this case—namely an adjustment of the local circulation. Another important factor, particularly at the greater depths, is the conduction of heat from the warmer to the colder tissues. This conduction probably accounts for most of the temperature rise at a depth of 4 centimetres.

From Fig. 5 it is seen that, as we enter the tissues from the skin, the gradient is at first negative, next becomes positive and then becomes negative again. American workers have reported a positive gradient in the first few millimetres next to the skin in the human body. This difference from our results is possibly due to the difference in experimental technique. In our case, the skin is covered by the surface of the applicator so that cooling does not readily occur. In the American experiments the skin was well separated from the applicator, and evaporation of perspiration, and also convection, would keep the skin temperature much lower. In the latter case, therefore, the difference between skin and deep temperature may be fairly high, and the dangers of deep burning are greater. With our applicators discomfort due to skin temperature acts as a check on the power-level adjustment of the apparatus.

The relationship of temperature with time depends upon the area irradiated and, with the same power dissipated throughout a greater volume, the time to reach the peak temperature is longer. This has been checked with our larger applicator.

Relation between temperature and depth

If no disturbing effect occurred, such as conduction to neighbouring tissues or unequal absorption due to lack of homogeneity of the tissues, then the temperature–depth curve should show an exponential temperature drop with depth. In actual fact, the distribution, due to the above effects, is much more suitable from the clinical point of view, since the heat is more uniformly distributed than it would be with an exponential distribution.

The experiment with the rabbit certainly calls for further work. It was expected that a metallic foreign body would not absorb energy, and would therefore not be heated. This we still believe to be so. The metal plate was inserted at the depth where the maximal rise of temperature would be expected. It may well be that the coagulation necrosis noticed near the plate would also occur in the absence of the plate, and experiments to clear up this point are in progress. An explanation in terms of standing waves, set up in the tissues by the plate, is plausible but conjectural at this stage.

Pulsed or continuous radiation

Finally, it must be borne in mind that all our results have been obtained with pulsed radiation. A point to be investigated is whether the biological effects of continuous-wave radiation are the same as those of pulsed radiation providing the same power. We believe that there will be no difference until the peak power of pulsed radiation is much higher than that used by us. Furthermore, in comparing our results with those of other workers, differences in wave-length must be considered. Water absorption changes but slowly between 12 centimetres' and 10 centimetres' wave-length and, if we ascribe most of the heating of tissues to absorption of water, there should be little difference in the results obtained at either of these wave-lengths. Below 10 centimetres in wave-length the radiation is absorbed more strongly in water as the wave-length decreases, the penetrating power decreasing steadily. In the near future we propose to investigate the effects of 3-centimetre micro-waves on tissues.

Conclusions

At this stage we may pause to consider what the possible future uses of micro-waves in medicine may be. With present apparatus, the heating effect is confined to the first few centimetres below the skin, being more penetrating than radiant heat or infra-red radiations, but much less so than short-wave diathermy. Accurate measurement of dosage appears to be practicable, and a very localized field may be obtained. It therefore appears to be unlikely that micro-waves can replace short-wave diathermy in the treatment of large areas or of deep-seated lesions. On the other hand, micro-waves may have a valuable part to play in the treatment of ophthalmic conditions, sinusitis, localized septic lesions, and the more superficial type of "rheumatic" disorders.

We hope, in the near future, to build a portable continuous-wave apparatus, incorporating the same features as our existing apparatus and suitable for clinical trials. In addition, we are considering the possibility of constructing special applicators for the treatment internally of the external auditory meatus, nares and cervix, and for treating fistulae and septic sinuses. We believe that it is along these lines that micro-wave therapy can be developed most usefully.

Summary

Current literature on micro-wave therapy is briefly reviewed.

A new method of irradiation is described, and the thermal effect on human tissue is recorded.

The results of overdosage in the laboratory animal are described, and a preliminary observation is made upon the effect of a metallic foreign body in the field of irradiation.

These results, together with the future possibilites of micro-waves in medicine, are discussed.

ACKNOWLEDGEMENTS

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SYSTEMIC THERMOTHERAPY

WITH SPECIAL REFERENCE TO HOT-AIR BATHS*

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IT IS not possible to discuss in this paper details of all the forms of systemic heat treatment ; I shall only try to illustrate some of its problems by using the example of a special type of general thermotherapy, which is different from pyrexial treatments of a duration of many hours. Some observations and results in this special case will help us to understand better the general basis of systemic thermotherapy in all its forms.

Apart from warm water and from the radiant heat emitted by a fire, hot air is probably the oldest means of heating the human body ; certainly, it also has been applied in treatment of sick men since ancient times. Yet, during a long period, the scientific basis of this therapeutic procedure did not find much interest on the part of the medical profession, although the basic problems had been clearly realized as long as 174 years ago, as is shown by the outstanding papers which Charles Blagden published in the *Philosophical Transactions of the Royal Society* in the year 1775.

The Sauna hot-air bath

The special form of systemic thermotherapy which we have investigated recently, at the Institute of Physical Therapy of the University of Zurich, is the Finnish hot-air bath, the so-called Sauna bath (Ott, 1948). It has survived as a prototype of those hot-air baths which, until the end of the eighteenth century, were very popular in many countries of central and eastern Europe. In Switzerland, since 1941, the Sauna bath has become extremely popular ; there are now more than 150 public Sauna-bath establishments, not including the many private Sauna baths—a relatively large number in a small country of some 4,000,000 inhabitants !

The interesting history of this type of sweating-bath must be omitted in this paper. The most important technical details may be dealt with briefly. A rather small room with rough wooden walls, fitted with high benches big enough to accommodate several adults sitting and lying, is heated by means of a very hot stove to an air temperature of about 80° C. The relative humidity of the air can be varied by means of water sprayed on to the stove, but it is normally a low one (5–15 per cent). The average duration of a bath is 20 minutes ; the hot-air bath usually is followed immediately by a cold spray or by a short cold immersion bath.

Traditional therapeutic effects

The following therapeutic effects of this kind of heat treatment have been claimed during the course of centuries.

(1) Quicker recovery after heavy physical work (effect of a single bath).
(2) Increase of physical fitness following a regular application (for example, once weekly) of the Finnish bath.
(3) Prophylactic effect against cold and infections of the upper respiratory tract.
(4) Healing effects in certain rheumatic diseases.
(5) Improvement in some chronic inflammatory diseases and metabolic disorders.

Our own clinical observations proved that these claims are—within reasonable limits—justified ; thus there was an obvious need to know more about the scientific bases of this empirically useful method.

Physical characteristics of the Sauna bath

For physiological reasons, the predominant characteristics of this type of heat treatment are defined by the high temperature and low relative humidity of the air. The latter is of outstanding importance for the thermo-regulation of the human body, because evaporation of water is the most powerful cooling mechanism of the human body, and because the cooling effect of evaporation is strictly dependent upon the humidity of the surrounding air.

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