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EFFECTS OF IMPLANTED METALS ON TISSUE HYPERTHERMIA PRODUCED BY MICROWAVES *

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Diathermy of wavelengths between 3 and 300 meters has been applied by the physical therapist since shortly after the first World War. In the application of diathermy, the technician has been cautioned to remove from the patient all surface metals which might be within the field of radiations. It was believed that the metals might cause a concentration of the field, thus producing burns.[1] Little work was done until recently to confirm this danger. In 1947 Lion[2] reported the field-concentrating effect of tantalum when immersed in electrolytes and irradiated with frequencies of 10 to 55 megacycles. He also demonstrated that it is possible to coagulate solutions of egg albumin at the points of field concentration. Etter, Pudenz and Gersh[3] implanted metals such as are used in surgery in animals and then exposed them to radiations of wavelengths of 8 to 24 meters. They concluded from histologic studies that, in the intact animal, destruction from heating did not occur in the tissues contiguous to the implanted metals. However, Lion pointed out that the depths at which the metals were implanted in these experiments may have been too great to permit a temperature increase sufficient to cause burning.

The recent approval by the council on Physical Medicine of the American Medical Association[4] of a microwave machine generating radiations of a frequency of 2,450 megacycles (12.25 cm. wavelength) offers another field of diathermy to be investigated. Some reports have been published on the biologic effects of microwaves.[5] None of these has made any reference to the effect of irradiation on tissue containing implanted metals. The following studies were conducted to determine whether any difference exists between the heating pattern produced by irradiation with microwaves in tissues containing implanted metals and that in tissues with no implants.

Experimental Studies

In Vitro Studies. — Experiments were carried out on blocks of fresh beef liver to determine whether the presence of metal implants would alter the heating pattern resulting from irradiation with microwaves. The liver blocks were placed in boxes constructed from Plexiglas in order to provide uniformity in size and depth. The boxes were of the dimensions of 8 by 8 by 4 cm. and were made from material ¼ inch thick. Holes were drilled in a horizontal line every 0.5 cm. in a side of the container, 4 cm.

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1. Krusen, F. H.: Physical Medicine, Philadelphia, W. B. Saunders Company, 1941, p. 427.
2. Lion, K. S.: The Effect of the Presence of Metals in Tissue Subjected to Diathermy Treatment, Arch. Phys. Med. 28:345 (June) 1947.
3. Etter, H. S.; Pudenz, R. H., and Gersh, I.: The Effects of Diathermy on Tissues to Implanted Surgical Metals, Arch. Phys. Med. 28:333 (June) 1947.
4. Apparatus Accepted by Council on Physical Medicine, Chicago, American Medical Association, 1947.
5. Dailey, E. L.: A Clinical Study of the Results of Exposure of Laboratory Personnel to Radar and High Frequency Radio, U. S. Nav. M. Bull. 41:1052 (July) 1943. Kemp, C. R.; Paul, W. D., and Hines, H. M.: Studies Concerning the Effect of Deep Tissue Heat on Blood Flow, Arch. Phys. Med. 29:12-17 (Jan.) 1948. Leyden, W. M.; Herrick, J. F.; Wakim, K. G., and Krusen, F. H.: Preliminary Studies on the Heating and Circulatory Effects of Micro-Waves — "Radar," Brit. J. Phys. Med. 10:177 (Nov.-Dec.) 1947. Osborne, Stafford, L., and Frederick, Jesse N.: Microwave Radiation; Heating of Human and Animal Tissues by Means of High Frequency Current with Wavelength of Twelve Centimeters, J. A. M. A. 137:1036 (July 17) 1948.

from the top, to permit the insertion of thermocouple needles. Vertical slits were made at fixed distances from the front of the box so that a metal plate could be implanted after the liver had been arranged in place. Various-sized plates made from stainless steel were employed as metal implants.

All temperature measurements were made by insertion of an iron-constantan thermocouple needle of the type described by Tuttle and Janney.[6] The thermocouple potentials were measured to the nearest 0.1 degree centigrade on a Leeds-Northrup potentiometer.

The generator used in all the experiments produced a continuous microwave of 12.25 cm. wavelength, or 2,450 megacycles. Its maximum output was 125 watts. By the use of a variac, any desired percentage of the maximum output could be obtained. The wave guide used was the corner type reflector, which was placed at a distance of 3 cm. from the surface to be irradiated. The irradiation time for the in vitro experiments was ten minutes, and the power output was 80 per cent of the maximum, or 100 watts. Temperature measurements were made at the surface of the liver, at designated depths and in front and behind the metal implant immediately before and after ten minutes of irradiation. Control experiments were made on a block of the same liver subjected to the same pattern of irradiation but without metal implants.

The first series of experiments with liver was designed to determine whether the size of the implanted metal plate would affect the temperature increase resulting from the irradiation. It had been suggested that greater heating would result if the plates were equal in diameter to either one or one-half times the wavelength in the liver.

The wavelength in liver was determined as follows:

$$\text{Wavelength in liver} = \frac{\text{wavelength in air}}{\sqrt{\text{dielectric constant of liver}}} = \frac{12.25}{\sqrt{78}} = 1.39$$

Two round plates were then made from 26 gauge stainless steel. When corrected for capacitance, the diameters of these plates were 1.36 and 0.68 cm. A third stainless steel plate (6 by 6 cm.) was included in this series. The plates were implanted at a depth of 2 cm. from the surface to be irradiated. Temperatures were taken at the surface of the liver, at a depth of 1 cm. and in front of and behind the metal implant immediately before and after ten minutes of irradiation. A control group of experiments was performed at the same time by irradiating liver containing no implant. In this series the temperatures were taken in the same manner: namely, on the surface, at a depth of 1 cm. and at a depth of 2 cm.

A comparison of the temperature increases in the liver with and without metal implants can be seen in chart 1. When the round plates (1.36 and 0.68 cm. in diameter) were implanted, the average temperature increases were greater than those found in the controls. The increases at the surface and behind the plate were not significantly different from those in the controls. However, the increases at 1 and 2 cm. in front of the plate were significant. The levels of confidence were 0.1 and 1 per cent, respectively. None of the temperature increases found when the 6 by 6 cm. plate was implanted was significant when compared with controls. In general, the greatest degree of temperature increase was found at the surface, the increase being inversely related to depth.

Since no gross tissue damage was observed in the previous series of experiments in which the metal was implanted at a depth of 2 cm., the implantation depth was decreased to 0.5 centimeter. The Plexiglas containers and the three plates used in the previous series of experiments were also employed in this study. In addition a 2.5 by 2.5 cm. stainless steel plate was included. Control experiments (with liver in which no metals were implanted), also were carried out. The temperatures were taken at the surface, in front and behind the plate in the implant experiments. In the controls, temperatures were taken at the surface and at a depth of 0.5 cm.

Chart 2 is a comparison of the average temperature increases at the different depths in liver with the plates implanted at a depth of 0.5 cm. The average temperature increases at all depths with the 6 by 6 cm. plate implanted were significantly greater (0.1 per cent level of confidence) than the

6. Tuttle, W. W., and Janney, C. D.: The Construction, Calibration and Use of Thermocouples for Measuring Body Temperature, Arch. Phys. Med. 29:416 (July) 1948.

controls. The liver appeared to be coagulated between the surface and the front of the plate in an area roughly the size of the plate. There was also coagulation for a short distance behind the plate in the same area. When the 2.5 by 2.5 cm. plate was implanted, coagulation appeared between the surface of the liver and the front of the plate. However, coagulation was not always present behind the plate. The average temperature increases at

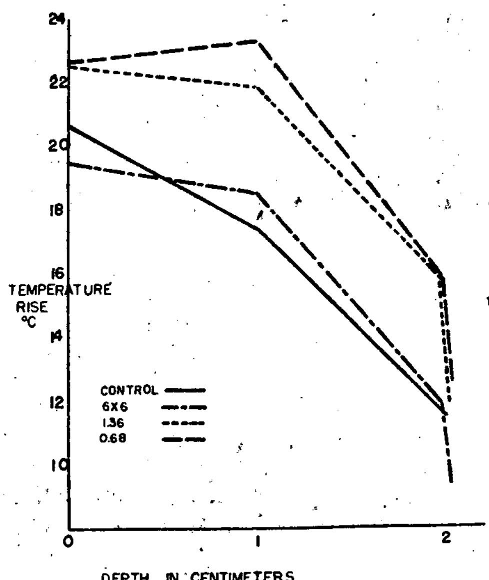

Chart 1. — Temperature increases in liver tissue in vitro following irradiation in Plexiglas boxes with 12.25 cm. microwaves. Stainless steel plates were implanted at a depth of 2 cm. Controls contained no metal plates.

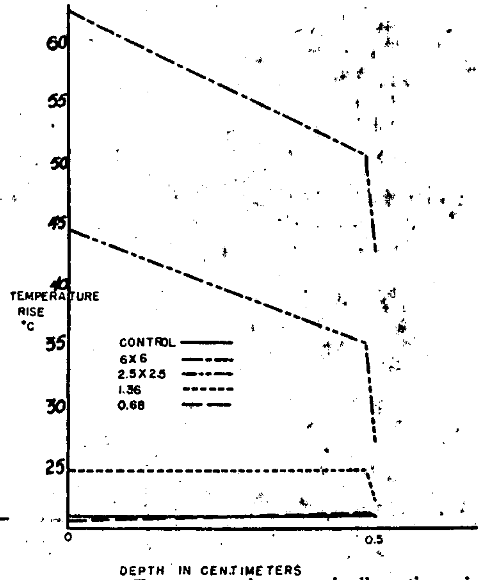

Chart 2. — Temperature increases in liver tissue in vitro following irradiation in Plexiglas boxes with 12.25 cm. microwaves. Stainless steel plates were implanted at a depth of 0.5 cm. Controls contained no metal plates.

the surface and in front of the plate were significantly higher than at corresponding depths in control experiments without metal implants (level of confidence 1 per cent). The same was true for temperatures behind the plate (level of confidence 2 per cent).

The average temperature increases with the round plate 1.36 cm. in diameter were significantly different at the surface (level of confidence 2 per cent) and in front of the plate (level of confidence 5 per cent). The increase in temperature behind the plate was not significant. In two experiments slight coagulation was observed between the surface and the front of the plate, but none was found behind the plate in any of the experiments. No significant increases in temperature occurred when the round plate 0.68 cm. in diameter was implanted. In each group of experiments included in this series, except the one in which the plate 0.68 cm. in diameter was used, the greatest average temperature increase was at the surface. The increase became less as the depth increased.

Experiments were carried out in which blocks of liver with Glisson's capsule intact were irradiated without Plexiglas covers. The purpose of this was to determine whether the results of the previous experiments could be attributed in part to the Plexiglas containers. Blocks of liver with and without implants of metal (6 by 6 cm. plates) at a depth of 0.5 cm. were irradiated as in the previous experiments except that the electromagnetic waves did not pass through a layer of Plexiglas.

Chart 3 gives a comparison of experimental and control data in this group. The average temperature increases in liver with metal implants were found to be significantly different from the increases in the controls at each depth (level of confidence 0.1 per cent). Coagulation was found between the surface and the implanted metal plate as well as behind the plate. The greatest temperature increase occurred at the surface, the increase diminishing as the depth increased.

In Vivo Studies. — A pattern of temperature increases following irradiation was established in the experiments conducted in liver tissue in vitro. Since the maximum temperature increases were developed when the 6 by 6 cm. stainless steel plate was implanted at a depth of 0.5 cm., it was decided to implant this plate under the abdominal wall and peritoneum of live rabbits. The thickness of these tissues was approximately 0.5 cm.

Urethane (1.75 Gm. per kilogram) was administered rectally for anesthesia. An incision was made in the midline of the abdomen and the plate inserted under the abdominal wall on the right side. Linen thread was used to suture the incision. The right side of the animal contained the metal, and the left side was used as the control. A total of 32 rabbits was irradiated. Animals 1 through 16 were irradiated first on the right and then on the left side for periods of ten minutes. The procedure was reversed for animals 17 through 32 — that is, the left side (control) was irradiated first and then the right side (containing the metal implant) was irradiated. This was done to determine whether the effects of the first irradiation period influenced the results of the subsequent irradiation of the contralateral side. Temperature measurements were taken immediately before and after each irradiation period. On the side containing the subsequent irradiation of the contralateral side. Temperature measurements were measured. The cutaneous and abdominal temperatures were taken on the control side. The power output used in this series of experiments was 62.5 watts.

The temperature changes produced by the stainless steel plate under the abdominal wall and peritoneum of rabbits and the control for this group are shown in chart 4. The temperature increase both at the cutaneous level and

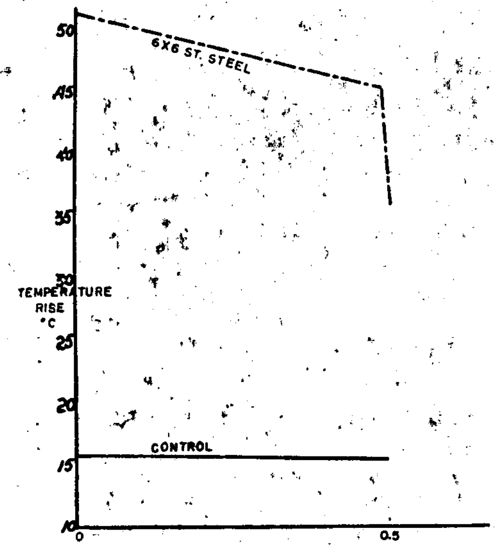

Chart 3. — Temperature increases in liver tissue with Glisson's capsule intact following irradiation with 12.25 cm. microwaves. The stainless steel plate was implanted at a depth of 0.5 cm. Controls contained no metal plate.

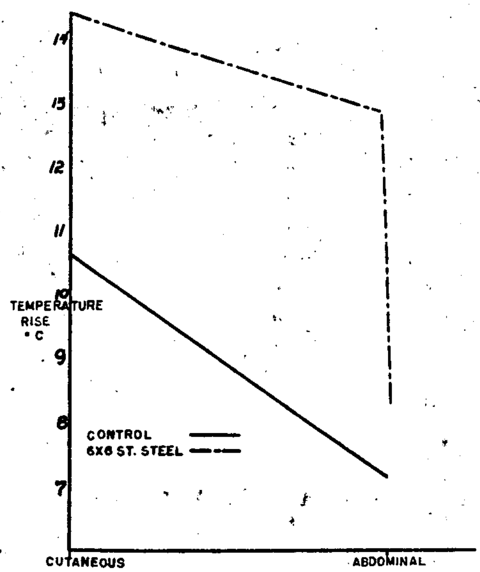

Chart 4. — Temperature increases in the abdominal wall of anesthetized rabbits following irradiation with 12.25 cm. microwaves. The stainless steel plate was implanted under the abdominal wall on the right side, and the contralateral side served as a control.

above the plate was significantly greater than in the corresponding depth in the control area (level of confidence 0.1 per cent). Under the plate the temperature increase was significantly greater than the control, at a level of confidence of 1 per cent. The tissue over the plate was usually edematous and appeared to be coagulated after irradiation. Edema was also present on the control side of 7 rabbits, but it was less severe than in the side with the stainless steel implant. The greatest average temperature increase was found at the cutaneous level, the increase diminishing with depth. This followed the pattern observed in most of the in vitro liver experiments.

Comment

The effectiveness of the metal implants in changing the heating pattern when the tissue is irradiated with 12.25 cm. waves appeared to vary with the size of the metal and the depth at which it was implanted. An explanation for the extremely high temperatures recorded in some of the experiments in which the metals were implanted at a depth of 0.5 cm. may be found in a reflected standing wave theory. The radiations penetrate the liver and upon reaching the plate are reflected back, setting up standing waves in the tissue between the metal implant and the surface. These energies are added to the original radiations, so that a much greater temperature increase results. Furthermore, a stainless steel plate, being a material with an electrical conductivity of 0.12 that of copper, would itself be heated. This could explain the high temperatures found behind the plate following irradiation, since the heat could be conducted from the plate to the tissue contiguous to it.

In the series of experiments in which the various-sized stainless steel plates were implanted at a depth of 0.5 cm. the temperature increase seemed to vary directly with the size of the implanted plate. This might be expected since the larger the plate, the greater the amount of reflecting surface; hence more standing waves were set up, resulting in a greater increase in temperature. However, when the metal plates were implanted at a depth of 2 cm., the amount of radiations reaching the plate was greatly diminished because of the absorption of the waves by the tissue. Consequently, the small amount of energy which penetrated as far as the plate did not set up many standing waves and, as a result, the temperature increases were not of the magnitude of those found when the plate was implanted at a less depth.

When the plates having a diameter equal to one or one-half times the computed wavelength in liver were implanted at a depth of 2 cm., there was a significant increase in temperature at a depth of 1 cm. and in front of the plate. This indicates that pieces of metal whose diameters either are equal to or are a fraction of the wavelength in the tissues may change the heating pattern. It falls within the realm of possibility that, as machines generating still shorter wavelengths are developed, small pieces of metal, such as are found in the fillings of teeth and in wire sutures, may cause increased heating sufficient to result in tissue damage.

It may be noted that the control pieces of liver irradiated through the Plexiglas had a greater temperature increase than those irradiated without the Plexiglas cover. This may be explained partly by the percentage of reflection of the radiations as they travel from one dielectric medium to another. From the formula $\left(\frac{\mu - a}{\mu + a}\right)^2$, in which a is the square root of the dielectric constant of the first material and μ is the square root of the dielectric constant of the second material, the percentage of radiation lost by reflection when passing from the first to the second material can be calculated. Therefore, when radiations pass from air (dielectric of 1) to Plexiglas (dielectric of 2.75) there is a reflection of 6.2 per cent. When they pass from the Plexiglas into the liver (dielectric of 78), there is added reflection of 43.6 per cent of the radiations, causing a total reflection of 49.8 per cent of the radiations when the liver was irradiated through the Plexiglas container. However, by similar calculation when the radiations passed from the air to the liver there was a loss of 63.5 per cent of the radiations. This means that theoretically there was a 13.7 per cent greater loss in radiation from reflection when the Plexiglas cover was omitted. This accounts, at least in part, for the more effective heating by irradiation through Plexiglas. The remainder may be accounted for by greater radiation of heat from a free surface than from one covered by Plexiglas.

The temperature increases found in the abdominal wall of the rabbits were not as great as those found in the liver either in the control or in that with the metal plate implanted. In the rabbits, the circulation was intact, so that the circulating blood could remove a considerable amount of heat and thereby dimish the increase which was measured at the end of the irradiation period. In addition, heat was being lost by radiation from the surface of the abdominal wall. Although the power of radiation used was within the safety range recommended for therapeutic use, gross tissue damage, which appeared to be coagulation, was observed in the tissue between the cutaneous surface and the metal plate. This tissue was found to be edematous after the irradiation. This edema was also seen in the control side of some of the rabbits, but the coagulation could not be detected grossly.

Conclusions

1. Under the conditions described in this report, irradiation with 12.25 cm. microwaves caused a greater increase in temperature in tissue containing metal implants than in control tissue.
2. The increase in temperature was of sufficient magnitude to cause gross damage in the tissue contiguous to the metal and between the metal plate and the surface of the tissue.
3. When implanted close to the surface, large metal plates caused greater heating than small ones.
4. The temperature increases were greater when the metal plates were implanted closer to the surface. The increase became less as the depth of implantation became greater.
5. The effects of metal implants depended upon depth of implant and upon the relationship of the size of the foreign body to the wavelength in tissue.
6. With careful use, it seems likely that during microwave irradiation there is little danger of burning a patient who either had metal implanted or metal imbedded in tissue. In most instances the metal is not as large or as close to the surface as described in this report. However, the physical therapist should be cautious in the application of microwave diathermy to tissue containing metal implants.