MULTI-FREQUENCY ELECTROMAGNETIC THAWING OF FROZEN KIDNEYS

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Abstract

The development of electromagnetic radiation techniques for thawing frozen organs is necessary in establishing frozen organ banks for surgical transplantation. Rapid and uniform thawing is a very difficult problem which is dependent upon kidney size, frequency of radiation, and power level. Failure to accomplish these thawing conditions results in excessive tissue damage. Experiments with canine and rabbit kidneys at two different frequencies are described.

The development of electromagnetic radiation techniques for thawing frozen organs is a key feature in establishing a procedure for successful transplantation of organs obtained from a frozen organ bank. At the present time, kidney transplantations occur very infrequently because properly matched donor kidneys are not available at the time of need. However, a complete bank of possible donor organs could be maintained to remedy this situation if long-term preservation of viable organs could be achieved. Long-term preservation by freezing offers hope for development of these organ banks if satisfactory thawing techniques can be developed.

Very little successful work to thaw the organs has been accomplished because no satisfactory method is currently available to rapidly and uniformly thaw frozen organs. Electromagnetic radiation offers great hope in this area. The success of electromagnetic radiation to rapidly and uniformly thaw frozen organs depends on several parameters: (1) the frequency of radiation, (2) the modulation of radiation, (3) the applied power level, (4) the size of the organ, (5) the dielectric constant of the organ tissue, (6) the loss tangent of organ tissue, (7) the cryoprotectant level of drug in the organ, (8) the thermal state of the organ, and (9) the doping of the organ with a recoverable material. The use of high-power electromagnetic radiation at two or more frequencies simultaneously with field configurations specifically chosen to produce uniform and rapid heating offers promise for a new thawing technique for large organs comparable in size to human organs.

Uniform thawing of large frozen organs is difficult to achieve for several reasons. The electromagnetic properties of frozen and thawed tissue are different, causing large differences in power absorption between frozen and thawed tissue. A recently developed technique for the "IN VIVO" measurement of the electromagnetic properties of tissue was used to determine the relative power absorption of several types of tissue, including canine kidneys.[1,2] In addition, the thermal properties are different for frozen and thawed tissue, with resultant differences in tissue heating rate. The combined effects of these differences can produce thermal runaway as the organ thaws, with the outer surface "cooking" while the inside is still frozen. Therefore, both the applied power level and the time of heating are critical and must be carefully monitored and controlled. This effect, shown in Figure 1, has hindered many researchers using microwave ovens for thawing frozen organs.[3] An additional complication arises when the kidney is perfused with a cryoprotectant before freezing. The electromagnetic power absorption, dielectric constant, conductivity, and thermal tissue heating rate are affected by the concentration of the cryoprotectant. Since the use of a cryoprotectant is mandatory if successful preservation is to be achieved, the effects on the normal electrical characteristics and resultant heating rate for various concentrations of these agents must be determined.

Various schemes have been evaluated for controlling the heating rate of the center and the surface of kidneys by pulsing (turning on and off) the electromagnetic energy. Although this equalizes the heating in the center and on the surface, it results in a very slow heating rate because the center is heated by thermal conduction, rather than by direct radiation. Figure 2 shows an example of this effect. Because the heating rate due to conduction is very slow, massive destruction of tissue occurs due to ice crystal formation.[4] A very rapid heating rate for the interior of the kidney can be achieved by doping the center with a recoverable material. This technique uses low frequency 7 MHz radiation which penetrates through the entire kidney, but does not significantly heat the kidney directly. Small stainless steel spheres, one millimeter in diameter, which are placed in the medulla of the kidney before it is frozen are used for doping. Because the spheres heat very rapidly in the 7 MHz field, the center of the kidney thaws before the surface, as shown in Figure 3. A combination of microwave heating of the kidney surface and low frequency heating of the interior should provide the rapid, uniform thawing rate needed for thawing without damage.

Work which has recently been done on a thawing technique for rabbit kidneys has provided encouraging results. Experiments have shown that uniform thawing, which is necessary to prevent tissue damage, is attainable without the use of 7 MHz radiation. These organs are small enough to allow complete thawing with radiation at 2450 MHz because the penetration depth of the microwave radiation at this frequency is greater than the thickness of the kidney.

Measurements made using a power of 100 watts indicate a useful penetration depth of approximately two centimeters at 2450 MHz. The approximate thickness of the rabbit kidneys used for experimentation was 2.0 cm. This affords adequate penetration depth which resulted in the thawing rates observed in Figure 4. The thermal runaway experienced with canine kidneys subject to 2450 MHz radiation (Figure 1) does not occur, but the surface temperature does tend to rise at a higher rate than the temperature of the interior of the kidney (medulla).

An S-Band waveguide loaded with fused silica provided an efficient match between the source and the load. In addition, a rotator which alternates direction after each 360 degree rotation was located directly in front of the radiator. Figure 5 presents the results obtained using a dielectric loaded radiator at 2450 MHz and kidney rotation. Uniformity of thawing using this technique was checked using a temperature sensitive liquid crystal plate in conjunction with thermistors implanted in the center and just under the surface of the kidney. The results indicate that essentially uniform thawing was achieved.

Various types of thermocouples and thermistors were evaluated for use in measuring temperature rise in the presence of an electromagnetic field. Thermocouples proved unusable because of focal heating in tissue adjacent to the device and excessive induced currents in the loads due to the RF field. The majority of these problems were obviated with the use of small bead thermistors having a diameter of only .42 centimeter.

Experiments to determine thawing rates achievable using higher power were performed on rabbit kidneys using the techniques and instrumentation described above. A power level of 1000 watts at 2450 MHz was employed and the results, shown in Figure 6, are extremely encouraging. Complete thawing of the kidney occurred in slightly less than 40 seconds which represents a heating rate of greater than 20 degrees centigrade per minute.

Future plans include experiments to determine the heating rate and uniformity of heating for rabbit kidneys that have been perfused with varying concentrations of cryoprotectants. Tests of tissue viability will also be made. Additional work will also include using a combination of 2450 MHz and 7 MHz radiation to thaw canine kidneys and the measurement of the electrical properties of frozen and thawed kidney tissue at microwave frequencies.

References

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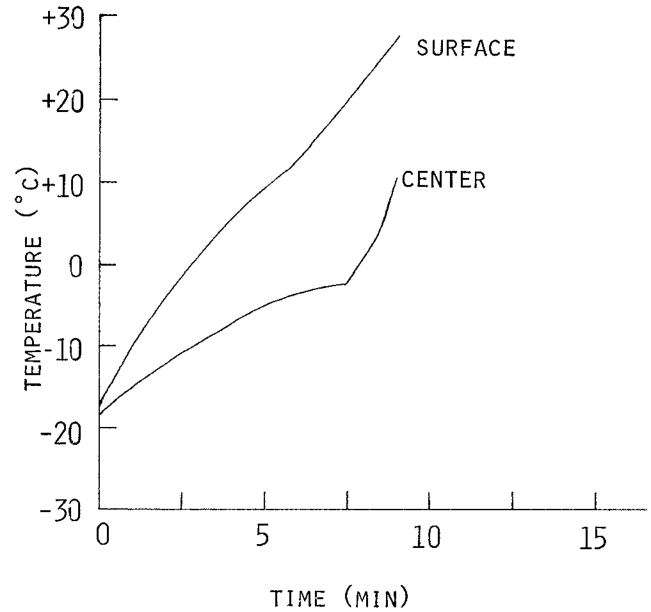

FIG. 1. RADIATION OF CANINE KIDNEY AT 2450 MHz USING 70 WATTS CONTINUOUS POWER.

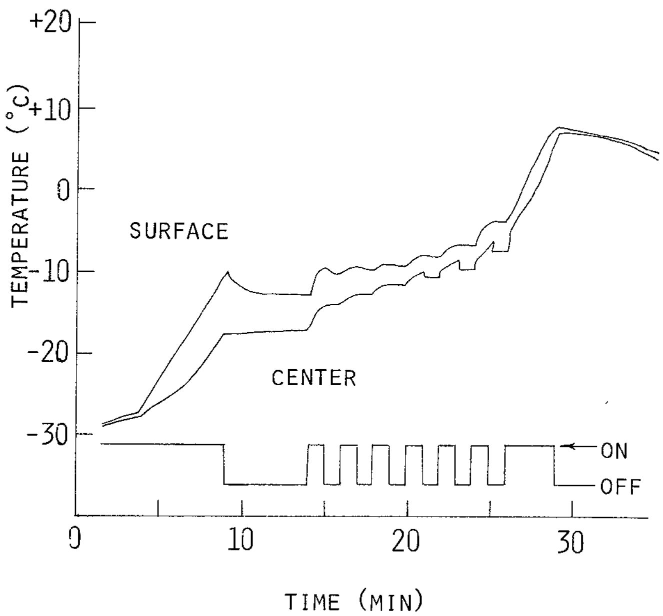

FIG. 2. RADIATION OF CANINE KIDNEY AT 2450 MHz USING 70 WATTS OF PULSED POWER.

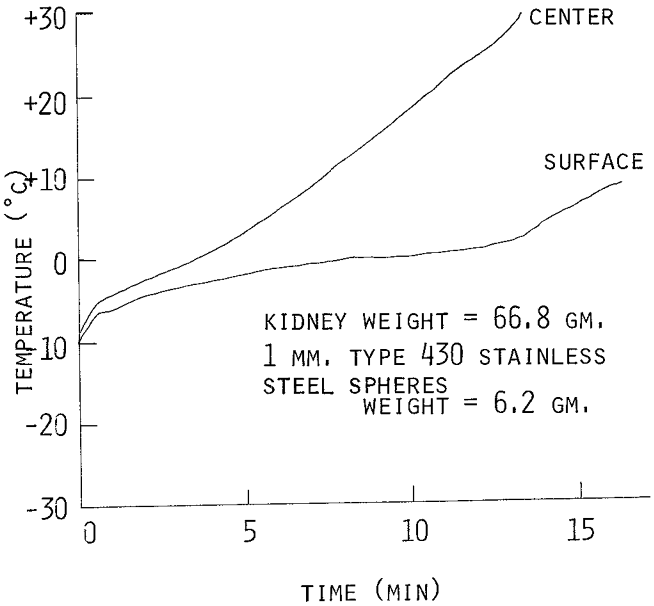

FIG. 3. RADIATION OF CANINE KIDNEY WITH STAINLESS STEEL SPHERES IMPLANTED IN PELVIS AT 7 MHz USING 500 WATTS CONTINUOUS POWER.

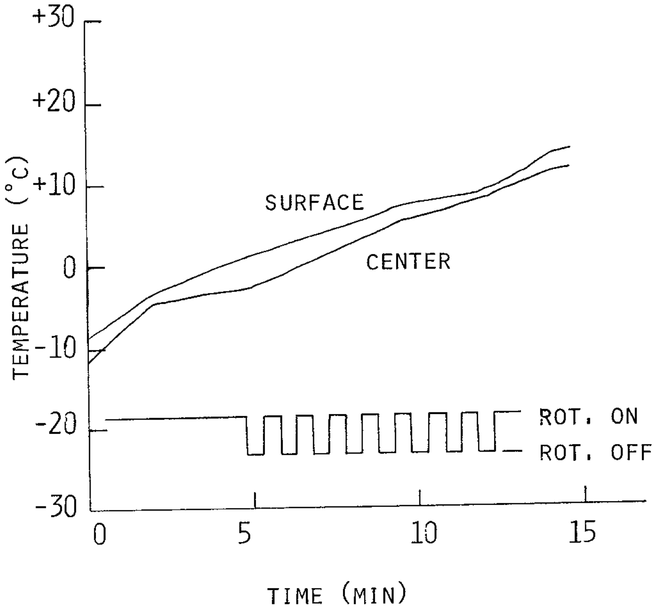

FIG. 5. RADIATION OF ROTATED RABBIT KIDNEY AT 2450 MHz USING 100 WATTS CONTINUOUS POWER.

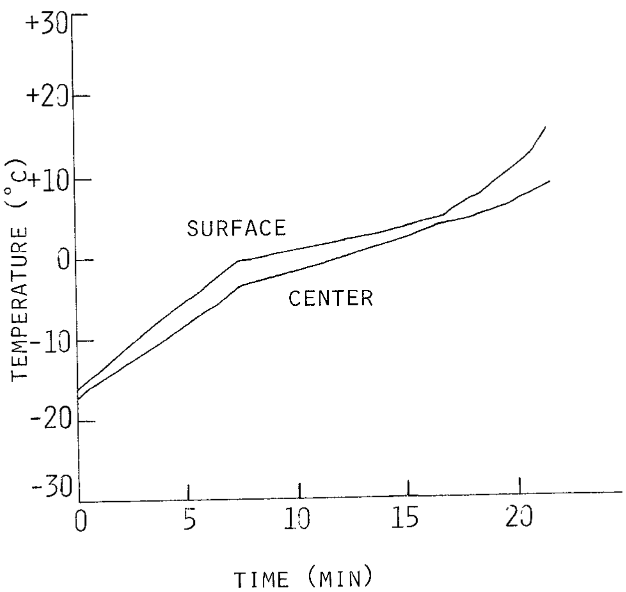

FIG. 4. RADIATION OF RABBIT KIDNEY AT 2450 MHz USING 80 WATTS OF CONTINUOUS POWER.

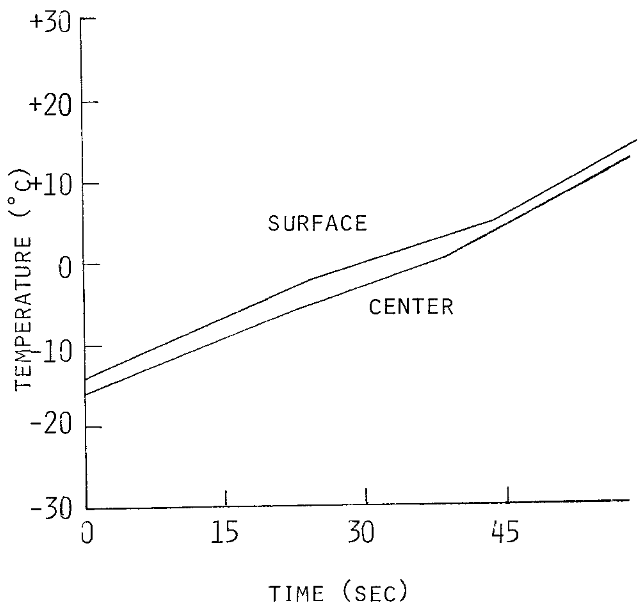

FIG. 6. RADIATION OF CONTINUOUSLY ROTATED RABBIT KIDNEY AT 2450 MHz USING 1000 WATTS CONTINUOUS POWER.