Temperature Dependence of Electrical Resistivity and Thermal Conductivity for a Gel Model of Nerve Tissue

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ABSTRACT: Our goal was to test for the temperature dependence of the thermal conductivity and electrical conductivity of a spinal nerve tissue surrogate. The model, which was a gel, was similar in the most important thermophysical properties to spinal nerve tissue. However, the variation of the properties with temperature, specifically thermal conductivity and electrical resistivity, were unknown. These two properties play a large role in how much heat is dissipated in the gel. After performing the experiments, we found that the thermal and electrical conductivity of the gel decreased as temperature increased. Applying this information to spinal revision surgery, we concluded that since heat will pass through the gel at a slower pace as temperature increased, surgeons will be able to operate under high temperatures with less thermal necrosis of the tissue than previously believed. However, for thermal ablation surgery, these results give negative implications because the tissue will not be as easily destroyed by intense heat as previously thought.

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1. INTRODUCTION

An important part of research is correctly simulating the conditions and parameters which actually occur in a real situation. An area of great importance where this is especially true lies in biologically related research. It is very difficult to perform experiments and collect data *in vivo*. In fact, in some cases it is impossible to run tests and experiments *in vivo* or even on a cadaver. With this in mind, an experimental model similar in thermophysical properties of tissue must be produced. We have previously developed a tissue surrogate based upon soy agar [7]. The purpose of this research is to establish the temperature dependence of thermal and electrical conductivity in the surrogate. Although thermal and electrical conductivities are published for a wide range of tissues, most of these data are at physiologic temperature (37°C). At this point in time, research on temperature profiles in human tissue typically has not accounted for changes in physical properties with temperature. Data has already been collected for thermal conductivity at 50°C [7]. Now we would like to cover a range of temperatures so that this gel can be used for future *in vitro* experiments that will be very close to actual *in vivo* procedures. When establishing temperature profiles, the tissue thermophysical properties may change with a change in temperature, as they do in most non-biological materials. It is important that our model properties are as close as possible to nerve tissue. It is expected that the thermal and electrical conductivity will both show a decrease as temperature rises since this is the behavior of most liquids. The degree in which the thermal and electrical conductivity changes for a tissue or a tissue model as the temperature rises remains unknown.

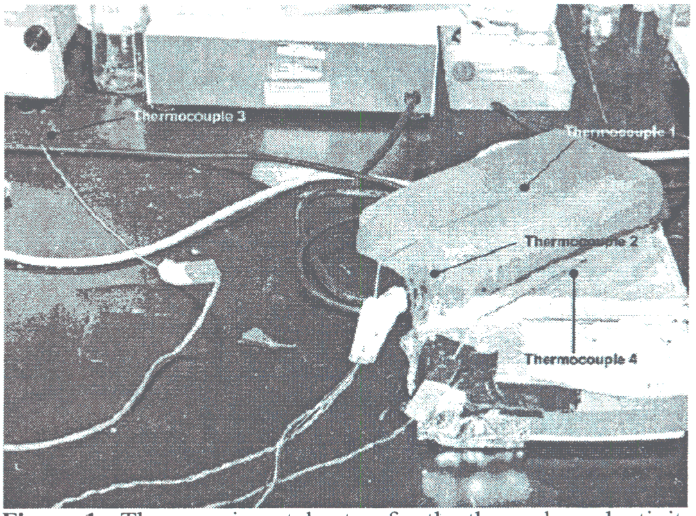


Figure 1. The experimental setup for the thermal conductivity test.

It is important that we establish this relationship accurately, because in order to accurately predict temperature profiles with computer models, the dependency of thermal and electrical conductivity must be known.

2. MATERIALS AND METHODS

2.1 Tissue Model

In order to make a model of the spinal nerve tissue, we made a gel consisting of 80 g of NaCl and 40 g of Tryptic Soy Agar (TSA) in a 1L flask of deionized water. We placed the flask onto a hotplate and added the NaCl first and used a funnel to add the TSA. The contents were left stirring in

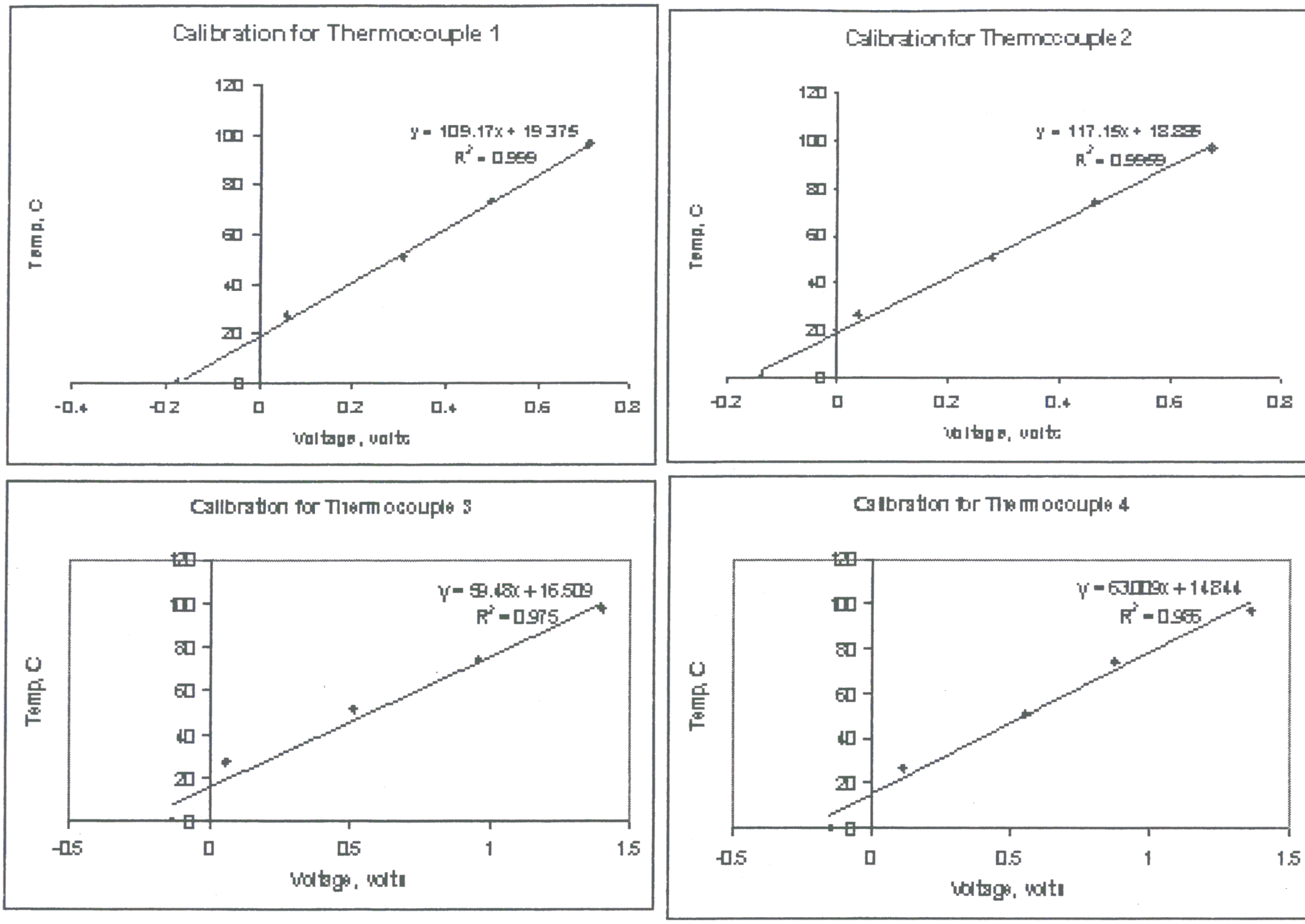


Figure 2. The graphs of the final calibrations of the thermocouples. The graph shows the temperature in °C, versus the voltage output in volts for each of the thermocouples.

the beaker until the mixture turned from a thick, yellow, opaque substance to a more transparent solution. After the solution turned clear, the contents were poured into a baking pan and put in the refrigerator for at least 4 h before total solidification.

2.2 Data Acquisition

We used the data acquisition setup as described previously by Quinn *et al.* (2004) [6]. Because of difficulties in calibrating the RTDs of that arrangement, we employed thermocouples in this study instead. We set up a LabVIEW program to measure the temperatures at each 100^{th} of a second. As the program was executed, the temperatures were recorded and saved into Microsoft Excel for further calculations (Fig. 1).

2.3 Calibration

To calibrate the thermocouples, we placed all four of them in water and took one reading at several temperatures ranging from 20°C to 100°C (Fig. 2).

2.4 Thermal Conductivity

We formulated a thermal conductivity test in order to establish kappa (κ), the thermal conductivity constant. We placed a slab of the gel with dimensions of length=10 cm, width=9 cm, and height=3.9 cm on top of a Corning hot plate. Thermocouple 1 was placed in the top half of the gel, which had a distance of approximately 5 mm from the top of the gel. Then, thermocouple 2 was placed in the bottom half of the gel, about 3 mm from the hot plate, leaving a distance of about 3.1 cm between the two thermocouples. Next, thermocouple 4 was placed directly on the hotplate next to the gel to monitor the plate temperature, and thermocouple 3 was held in the air to measure the ambient air temperature (Figs. 1 and 3).

We then recorded the temperatures of the thermocouples while the hot plate temperature, measured by thermocouple 4, was approximately 30°C, until the temperature of thermocouple 2 matched that of thermocouple 4 and stayed at a steady state for about 10 min. This procedure took 2-3 h to complete because the gel heated up at a much slower

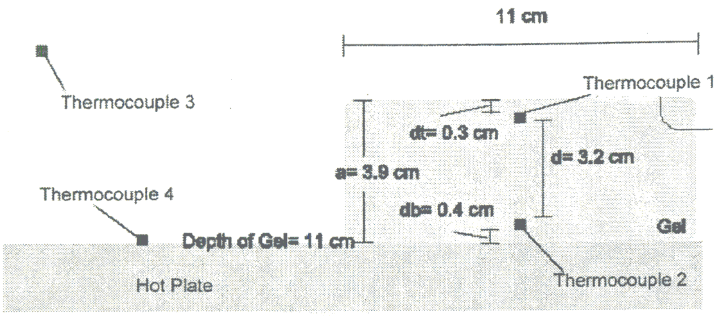
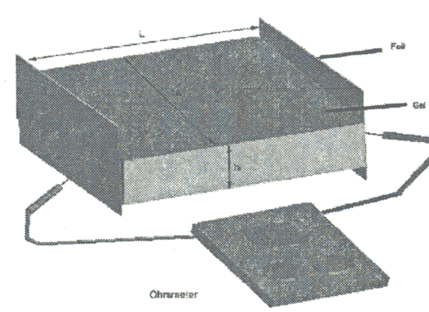


Figure 3. Quantities used in the equation (10).



EXPRESSION	VALUE
a	0.13 m
b	0.10 m
h	0.04 m
L	0.22 m
Tref	294 K

Figure 4. A diagram of the experimental setup used to measure the electrical conductivity and a chart of the diagram properties.

pace than the hotplate. This data was automatically put into a table in Microsoft Excel. The process was repeated at 40°C, 50°C 60°C and 70°C (Figs. 5, 6, 7, and 8).

2.5 Mathematical Modeling

To find κ (the thermal conductivity) we employ the following mathematical model (5).

$$\alpha \frac{\partial^2}{\partial x^2} = \frac{\partial u}{\partial t}, \qquad 0 < x < a, \ 0 < t$$

$$u(0,t) = T_o, \qquad 0 < t$$

$$-\kappa \frac{\partial u}{\partial x}(a,t) = h(u(a,t)) - T_1), \qquad 0 < t$$

$$u(x,0) = f(x), \qquad 0 < x < a.$$

Since we are at the steady state, the time derivative equals 0. We integrate twice, replacing u and its derivatives by v and its derivatives, and arrive at the following solution.

$$v(x) = A + Bx$$

The slope of the temperature profile may be related to the parameters of the problem as in equation:

$$B = \frac{T_2 - T_1}{[db - (a - dt)]} = h * \frac{(T_1 - T_0)}{(\kappa + h * a)}$$

the quantities in equation are referenced in Figure 3 [5, p 142].

Before solving for the thermal conductivity constant, we must first establish h, the heat transfer coefficient. We use the procedure outlined by Incropera and DeWitt [4]. There will be differing h values for both the vertical plate and horizontal plate of the gel. For our uses, only the horizontal plate value will be of interest. We begin by finding the Rayleigh Number for the horizontal plate:

$$Ra = \frac{g\beta(T_z - T_\infty)L^3}{v\alpha}$$

In the equation, the gravitational constant g=9.807 (m/s^2), the volume expansivity of air β=3.12 x 10^{-3}(K^{-1}), the surface temperature of the gel T_s=323 (K) for a hotplate temperature of 50°C, the ambient air temperature T_∞=294 (K), the length of the gel L= 10(cm), the kinematic viscosity of air v=15.89 x 10^{-6}(m^2/s), and the thermal diffusivity of air α=22.5 x 10^{-6}(m^2/s). Then by using the Rayleigh Number we can find the Nusselt Number with the following equation:

$$Nu = 0.54Ra^{1/4}$$

We calculated Ra=2.482 x 10^6. Finally, with the Nusselt Number we may now find a solution for our heat transfer coefficient by solving for h in the following equation:

$$Nu = \frac{hL}{k}$$

In the previous equation (9) k=26.3 x 10^3 (W/m K).

2.6 Electrical Resistivity

We began by testing the electrical resistivity of a tryptic soy agar gel with 40g of TSA and 1L of water. The electric potential was uniformly spread out across the gel by placing a small piece of aluminum paper at both ends of the gel (standard) just covering the end faces. (See Figure 4). Then the probes of an ohm meter were touched to the foil which yielded the raw resistance in ohms. The multimeter's accuracy was verified with 5, 50, 500, and 50,000 ohm resistors. Next, the resistivity of the gel was calculated from its defining equation .

$$\rho_e = \frac{R * A_{gel}}{L}$$

R is the raw resistance recorded in ohms; A_{gel} is the cross-sectional area of the gel; and L is the length of the gel. The cross-sectional area of the trapezoidal gel was determined by the following equation (3).

$$A_{gel} = \frac{1}{2}(a + b)*h$$

The quantity a is the width of the top face of the gel and b is the width of the bottom face of the gel. The height was represented by h. This procedure was then repeated for a gel with different NaCl concentrations until resistance values were as close to human tissue as possible. The best

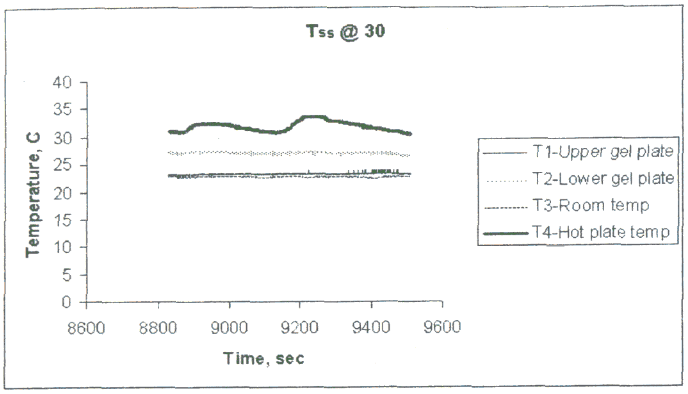


Figure 5. A plot of the temperature values for the different thermocouples versus time during the thermal conductivity test at 30°C. The thermocouple placement in Figure 3 corresponds with the legend.

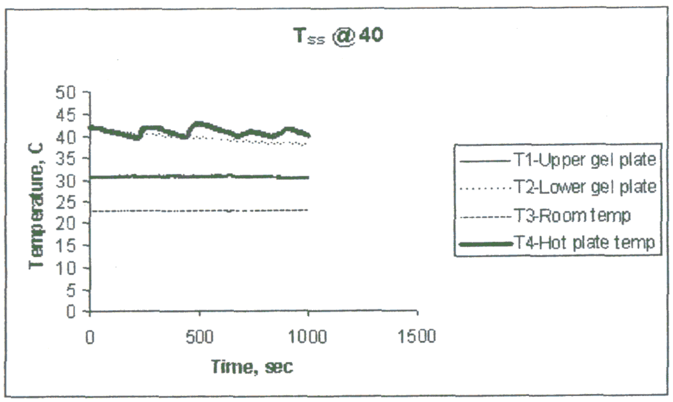


Figure 6. A plot of the temperature values for the different thermocouples versus time during the thermal conductivity test at 40°C. The thermocouple placement in Figure 3 corresponds with the legend.

electrical conductivity was found in a gel containing 80 g of NaCl, 40 g of TSA, and 1 L of water. The lowest value was about 1027 ohm*cm, which compares to 588 ohm*cm in human spinal tissue. (Fig. 9).

In order to vary the temperature of the gel and record the corresponding resistivity values, the following procedure was executed. A gel with 80 g of NaCl was cut in half. Then, both pieces of the gel were heated in a microwave for 45 sec. Both pieces were taken out and in one half was a thermometer to record temperature while the ohmmeter was used on the other half to record the corresponding resistance values.

After plotting the data, a temperature dependent expression for the resistivity which was developed by Shortley and Williams [8] was produced.

$$\rho(T) = \rho_0[1+\alpha(T-T_{ref})]$$

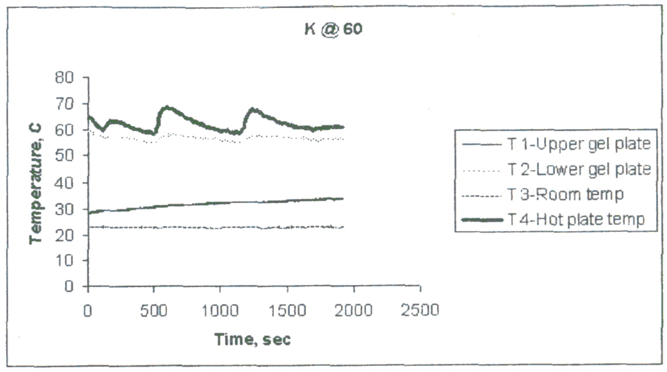


Figure 7. A plot of the temperature values for the different thermocouples versus time during the thermal conductivity test at 60°C. The thermocouple placement in Figure 2 corresponds with the legend.

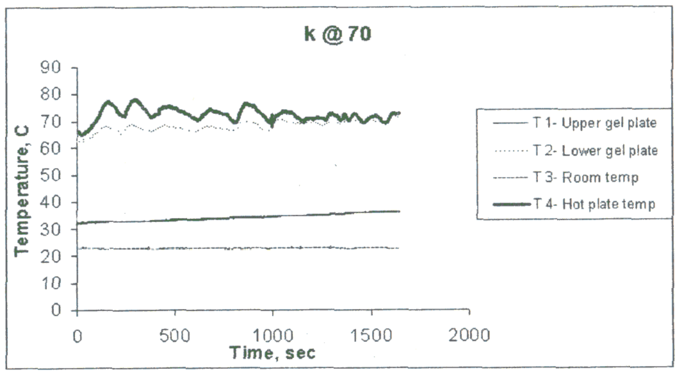


Figure 8. A plot of the temperature values for the different thermocouples versus time during the thermal conductivity test at 70°C. The thermocouple placement in Figure 3 corresponds with the legend.

3. RESULTS

3.1 Thermal Conductivity

After running the thermal conductivity test at 30°C, 40°C, 50°C, 60°C, and 70°C, the data acquired were put in the equations shown in the mathematical model. Using a program written in MathCAD, we were able to calculate the value of κ, the thermal conductivity, at each of the five temperatures. A graph of thermal conductivity of the gel versus the temperature is given in Figure 10. One clearly sees a monotonic decline of thermal conductivity with temperature.

3.2 Electrical Resistivity

A plot of resistivity is given in Figure 11. The resistivity increases linearly with temperature. From linear regression of the data to equation, the values for α and ρ_0 were found to be 0.01 K^{-1} and 1633.1 ohm*cm respectively.

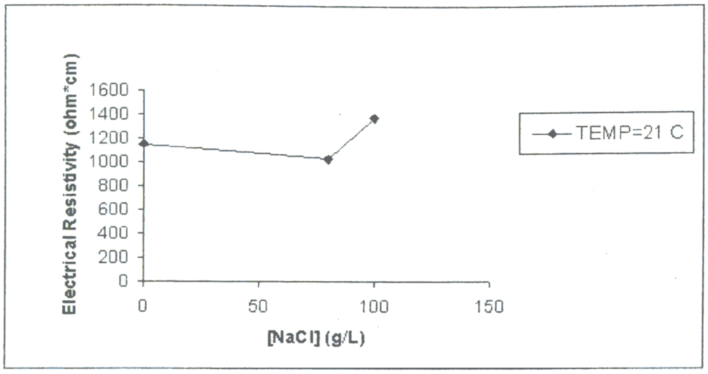


Figure 9. A graph showing the resistivity trend for different NaCl concentrations in the gel.

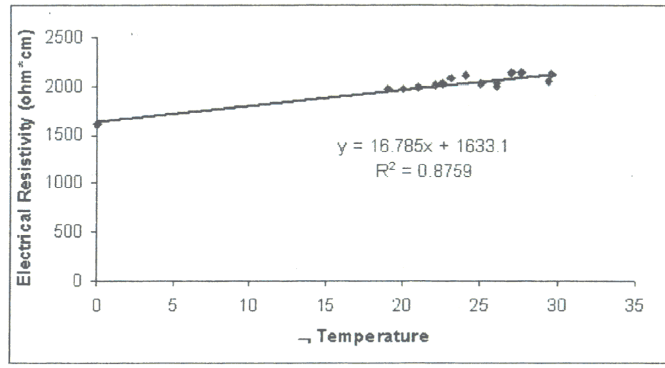


Figure 11. The change in electrical resistivity with a temperature rise.

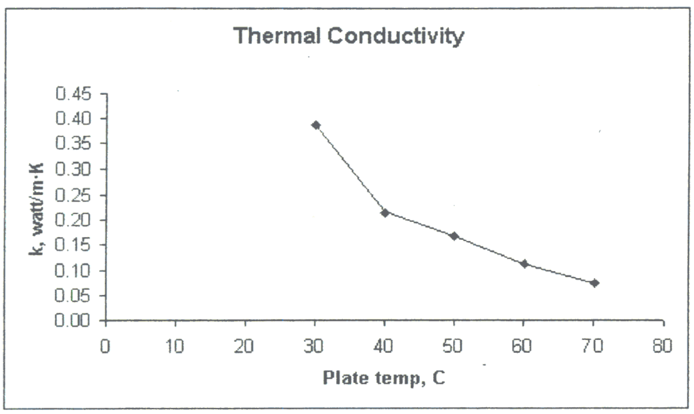


Figure 10. The thermal conductivity values of the gel at 30°C, 40°C, 50°C, 60°C, and 70°C are plotted and there is a visible decrease in their values.

4. DISCUSSION

In the case of most liquids, both the thermal conductivity and electrical conductivity decrease with increasing temperature. It is also known that these relationships exist in some solids also. However, our gel and living tissue itself are neither strictly solid nor liquid. We anticipated that our gel model would behave as a liquid under most conditions. After experimentally gathering thermal and electrical conductivity data that varied with temperature, it was apparent the gel model exhibited liquid-like behavior with respect to these two properties. It was found that the thermal conductivity and the electrical conductivity both decreased as temperature rose. This was not unexpected, since a large part of the gel and tissue is water. This was important for assessing the validity of our data. Here we note the consistency of our results with the accepted theories of thermal and electrical conductivities [2]. The intermolecular spacing is larger and the molecule movement is much more random in solids than in liquids. Therefore, the thermal energy transport becomes less effective as the gel gets warmer and warmer. The same explanation applies to electrical current as well.

The observed behavior of thermal and electrical conductivity of the tissue model and in living tissue has beneficial implications for spinal revision surgery. The volume of the heat-affected zone is less than if the thermal and electrical conductivities were constant. On the other hand, this behavior has negative implications for thermal ablation surgery. Thermal ablation surgery removes tumors by inserting a needle with a hot, non-insulated tip through the skin. The energy at the exposed tip causes ionic agitation and frictional heat, which leads to cell death and necrosis, destroying the tumor. Because the thermal and electrical conductivity of the spinal nerve tissue decreases with increasing temperatures, the intense heat produced by the needle tip will destroy less tissue than if the thermal conductivity and electrical resistivity were constant.

5. CONCLUSION

After performing the experiments, we found that the gel exhibited the thermal and electrical conductivity properties of a liquid with respect to temperature dependence. Our original hypothesis that the gel behaves as a liquid is supported, and is consistent with current published data about the inverse relationship of electrical and thermal conductivities with temperature.

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