# Thermal Property Measurement of Swine Atrium

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**Abstract**

Thermal conductivity, thermal diffusivity were measured in the atrium of a swine heart. Radiofrequency (RF) catheter ablation in an atrium has rapidly emerged at the treatment of symptomatic reentrant arrhythmia associated with accessory pathway or Atrioventricular (AV ) node conduction. The thermal properties of an atrium are definitely necessary for these treatments because, in thermal treatments, conductivity and diffusivity are significant factors in the relationship between the applied RF power and the resulting atrium temperature rise. Thermal properties were measured using a self-heated thermistor probe. Thermistor probes were inserted into the tissue of interest and were used to supply heat within the tissue as well as to monitor the temperature rise in the tissue. The measurements were performed at temperatures of 25, 37, 50℃. Atrium thermal conductivity ranged from 5.17 ± 0.12 mW/cm℃at 25℃ to 5.33 ± 0.08 mW/cm℃ at 37℃. Atrium thermal diffusivity ranged from 0.00132 ± 0.00007 $cm^2$/sec at 25℃ to 0.00138 ± 0.00003 $cm^2$/sec at 50℃. This paper also present the thermal property comparison of both chambers of a heart (ventricle and atria).

**Key words :** Thermistor probe, heart thermal property, radiofrequency catheter ablation

## Ⅰ. INTRODUCTION

Thermal properties of biological tissues including human organ tissue are important physical values in diagnosing or treating various diseases[13-15]. Among other probe methods, thermal probe techniques are commonly used to measure the thermal conductivity and the thermal diffusivity of biomaterials[1-10]. These approaches utilize a thermistor bead either as a heat source or a temperature sensor to measure the thermal properties of the biomaterials. Various thermal diffusion probe techniques have been demonstrated by Chato's[1]. Physically, for all of these techniques, heat is produced to the tissue at a certain location. Later it is dissipated by conduction through the tissue, or by convection with the blood perfusion.

For minimally invasive measurement, thermal probes should be constructed by placing a miniature thermistor at the tip of a plastic catheter. The volume of tissue over which the measurement occurs relies on the surface area of the thermistor. Electrical power is delivered to a spherical thermistor positioned invasively within the tissue of interest to induce heat generation. An assumption is set for the tissue to be homogeneous within 1 mL around the probe. The electrical power and the resulting temperature rise are measured by a microcomputer-based instrument. Thermal properties are derived from temperature and power measurements using equations that describe heat transfer in the integrated probe/tissue system.

The following sevaral complexities describe difficulty in the determination of thermal properties. First, tissue heat transfer includes several factors; conduction, convection, radiation, metabolism, evaporation, and phase change. It is difficult but needed to decouple these different heat transfer mechanisms. The accuracy of the perfusion measurement relies on a realistic thermal model. Second, the mechanical and thermal interactions between the probe and tissue involve complex interactions, and one must properly model to achieve accurate measurements. With the insertion of the probe into living tissue, a blood pool may form around the probe because of the mechanical trauma. Tissue damage due to probe insertion may also occur in vitro. Third, the tissue structure may be quite heterogeneous within each sample. Thus, the

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probe (which returns a single measurement value) can only provide measures of a spatial average of the tissue properties surrounding the active elements. Unfortunately, the spatial average is frequently very nonuniform[8]. The probe is most sensitive to the tissue immediately in contact. This fact yields importance of controlling this effective measurement volume. If the effective volume is too small, then the measurement is highly sensitive to the mechanical/thermal contact between the probe and tissue. In the other case, the effective volume is too large, then the measurement is sensitive to the boundary conditions at the surface of the tissue sample. Fourth, there are significant variation between sample to sample and species to species. One must be careful when extrapolating results obtained in one situation to different situations.

Accurate measurements of thermal properties are required in order to develop realistic transient thermal models. These models assume importance with increasing use of hyperthermia and therapeutic procedures based on heat delivery. Accurate properties are also required to simulate techniques like radiofrequency, microwave, laser, and ultrasound therapies on tissues. The properties presented in this paper can be used to generate thermal models for radiofrequency cardiac ablation in swine myocardium.

## II. METHODS

The thermal diffusion probe was developed by Chato[1], Balasubramaniam and Bowman[5] to measure the thermal properties of tissue. Valvano *et al*[10-12] have further improved the technique by designing and testing of a computer-based instrument for the measurement of thermal conductivity and thermal diffusivity of tissue. The method thermally perturbs the system and monitors the response. A single thermistor probe is inserted in the tissue of interest and the baseline temperature is monitored. The instrument first measures the baseline tissue temperature, $T_0$. Then, an electronic feedback circuit, shown in Fig. 1, applies a variable voltage, V(t), in order to maintain the average thermistor temperature at a predefined constant value, $T_h$. The feedback circuit drives the thermistor resistance, $R_h$, to equal the set resistance $R_{set}$. The transient electrical power delivered to the thermistor in order to maintain this elevated temperature ($T_h$) is described by

$$P(t) = A + B \cdot t^{-1/2} \quad (1)$$

where 'A' and 'B' are the steady-state and transient power, respectively, and 't' represents time. The applied power, P(t), varies during the 30-second transient period. Linear regression is used to calculate the steady state and transient terms in Equation 1.

This small amount of energy (typically about half a Joule) produced by the thermistor will cause no tissue damage or induce adverse systemic effects. The thermal properties of tissue are determined by fitting the probe heating data to a solution of the probe and tissue coupled bioheat transfer Equation 2.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial}{\partial r}V_m\right] + \frac{\psi - wC_t V_m}{K_m} = \frac{1}{\alpha_m}\frac{\partial V_m}{\partial t}; r \geq a \quad (2)$$

where r = radial distance in spherical coordinates (cm)

$V_m$ = temperature difference $T - T_0$ (℃) in tissue medium

$= Q_{met} + wC_t(T_t - T_0)$

$w$ = tissue perfusion (g/mL-s)

$C_t$ = specific heat (W-s/g-℃) in tissue

$K_m$ = thermal conductivity (w/cm-℃)

$\alpha_m$ = thermal diffusivity ($cm^2/s$)

$t$ = time (s)

$Q_{met}$ = metabolic volumetric heat exchange (W/mL)

$T_t$ = temperature (℃) in tissue

$T_0$ = initial temperature (℃)

$a$ = spherical probe radius (cm)

The following equations are used to calculate thermal conductivity ($k$) and diffusivity ($\alpha$) :

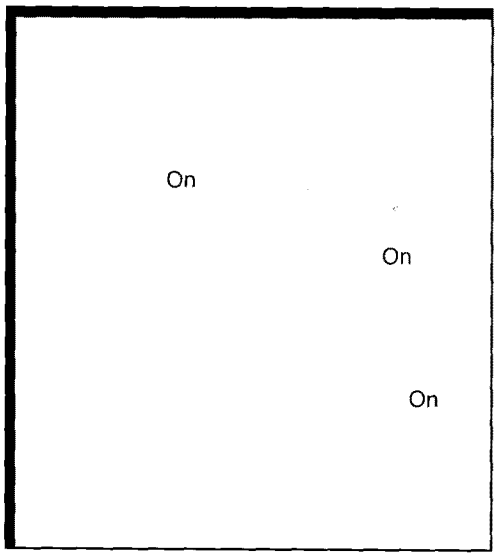


**Fig. 1.** Electronic feedback circuit used to heat the thermistor to a constant temperature.

$$k = \left[ \frac{1}{4\pi\alpha\left(\frac{\Delta T}{A}\right) - \left(\frac{1}{5k_b}\right)} \right] \quad (3)$$

$$\Delta T = T_h - T_s \quad (4)$$

$$\alpha = \left[ \frac{a}{\sqrt{\pi}\frac{B}{A}\left(1 + \frac{k}{5k_b}\right)} \right]^2 \quad (5)$$

$T_h$ and $T_s$ are temperatures of the heater and the source, respectively. A and B are constants.

Since actual probe radius $(a)$ and thermistor probe thermal conductivity $(k_b)$ are difficult to determine exactly, calibration coefficients, $K_1, K_2, A_1$, and $A_2$, are utilized.

$$k = \left[ \frac{1}{K_1\left(\frac{\Delta T}{A}\right) + K_2} \right] \quad (6)$$

$$\alpha = \left[ \frac{A_1}{\frac{B}{A}(1 + A_2 k)} \right]^2 \quad (7)$$

These parameters are determined by operation of the probe in two materials of known thermal properties. Anhydrous glycerol (C3H8O3, > 99.5% by volume) and agar-gelled water are used since their thermal properties have been documented[10,11], and thermal properties for tissues lie between them. The probes are calibrated at the same temperature as the subsequent thermal property measurements so as to compensate for the temperature dependence of the material and the thermistor thermal properties. Simultaneous solution to two equations obtained from substituting thermal conductivity of water and glycerol into the equation 6 and 7 permits the calculation of $K_1, K_2, A_1$, and $A_2$. For the present study prior to running the instrument on the tissue the accuracy was tested against glycerol and agar gelled water. The accuracy of the measuring technique was 0.5% at lower temperatures. Tissue thermal properties are strongly affected by its constituents; in particular, water is a major factor. In addition, the internal structure of myocardial tissue may also affect thermal properties. Structurally, the myocardial fibers align along the contraction path. This heterogeneity may cause the thermal conductivity to have a directional component. The atrium is much thinner, smoother than the ventricle and also has much less muscles. These features may cause any different thermal properties.

## Ⅲ. SWINE EXPERIMENTS

The purpose of the experiment was to measure the thermal conductivity and diffusivity in the atrium of normal swine heart. The swine heart tissue was obtained from a local slaughter house. The location of the sample in the swine heart is displayed in Fig 2. Freshly excised heart was wrapped in plastic and stored in a cooler at about 5℃ within 5 minutes after death. The experiments were performed on the tissue on the same day. The following experimental protocol was used for all experiments. The right or left atrium of the heart was cut into approximately cubical pieces of between 15 and 25 g. Because the atrium of the heart is very thin (3 to 5 mm), most samples were excised from the upper part of atrial septum where is the thickest in the atrium (about 1 cm). The probes were then inserted into the tissue sections such that the thermistor was located in the center. The probe and tissue together were wrapped in two layers of plastic and then immersed in a flask of water. This flask was put into a bigger flask and then both of them were put in a water bath maintained at a constant temperature. The reason to use a bigger flask is to reduce any thermal noise caused by the water bath itself. The experimental setup with these beaker is illustrated at Fig. 2.

The experiments were performed at 25, 37 and 50 ℃. Above 50 ℃ protein denaturation is expected, but not included in this study. The same tissue was used for one cycle. The first cycle simply went from 25 to 37 and to 50 ℃. The second cycle started at 37 ℃, next 50 ℃ then 25 ℃. The third cycle was started first at 50 ℃, and then 25 ℃, 37 ℃. These three cycles were selected randomly. Three probes using Thermometrics P60DA102K thermistors, were used to measure the properties simultaneously in three fresh tissue samples obtained from different swine hearts. The properties presented are each an average of 10 measurements in a single tissue sample. Each experiment involved about 45 minutes of

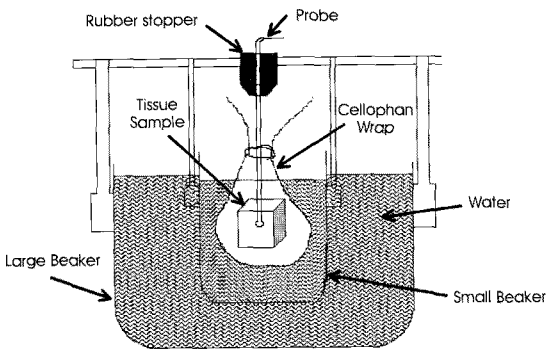


**Fig. 2.** Experimental set-up with two beakers.

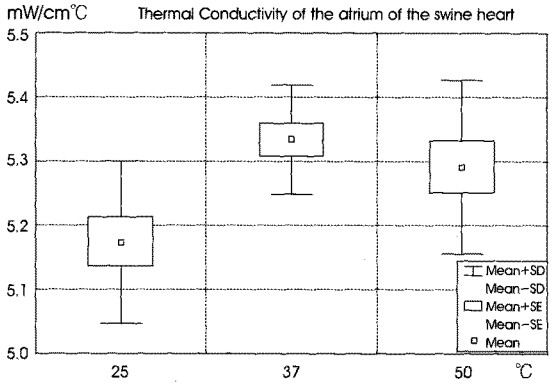


**Fig. 3.** Thermal conductivity of a swine atrium

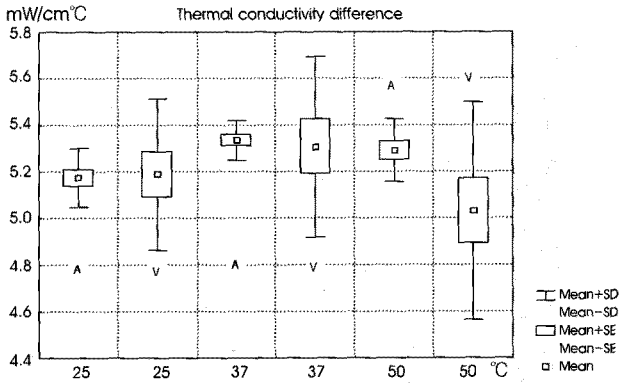


**Fig. 5.** Thermal conductivity difference between the atrium(a) and the ventricle(v)

heating and sensing. Each cycle took about 5 hours and whole experiment took about 2 weeks with 10 different swine hearts. The samples were weighed before the insertion of the thermistor into the sample and also after the experiment was completed. It was assumed that the weight loss in the tissue because of heating is due to the water loss. The water lost from the tissue, however, remained inside the plastic wrapper, which also prevented any water from entering the tissue from outside.

## Ⅳ. RESULTS & DISCUSSION

The purpose of the experiment was to measure the thermal conductivity and diffusivity in the atrium of normal swine heart. The measurement was performed in three different temperatures (25 ℃, 37 ℃, 50 ℃). The average conductivity (mW/cm℃) at each temperature was 5.17 (mW/cm℃) at 25 ℃, 5.33 (mW/cm℃) at 37 ℃ and 5.29 (mW/cm℃) at 50 ℃. The standard deviation of each temperature step was 0.1266 at 25 ℃, 0.0851 at 37 ℃ and 0.1353 at 50 ℃. The average diffusivity of each temperature was 0.001322 ($cm^2$/sec) at 25 ℃, 0.001363 ($cm^2$/sec) at 37 ℃ and 0.001389 ($cm^2$/sec) at 50 ℃. The standard deviation of each temperature was 7.6E-5 at 25 ℃, 3.8E-5 at 37 ℃ and 3.2E-5 at 50 ℃. Fig. 3 and Fig. 4 display the thermal conductivity and diffusivity of the swine atrium, respectively.

There was no statistically significant difference between thermal properties measured with the sequence 37 then 50 ℃ versus the sequence 50 then 37 ℃ (2 way ANOVA at a=0.05.) This coupled with the small amounts of weight loss suggest that water loss although extremely important did not affect these measurements.

There was a statistically significant difference in thermal conductivity measured at 27, 37 and 50 ℃ (a=0.05) as shown at Fig. 5. There was a significant difference in thermal diffusivity (Fig. 6) measured at 27 and 37℃ (a=0.05) as well as between 27 and 50℃ (a=0.05) but not between thermal diffusivity measured at 37 and 50℃.

A tissue's thermal properties are strongly affected by its constituents; in particular, water, protein and fat are major factors. In addition, the internal structure of myocardial tissue may also affect thermal properties. The constituents and the

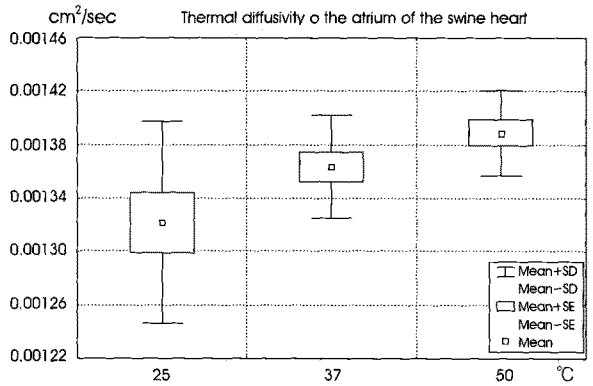


**Fig. 4.** Thermal diffusivity of a swine atrium

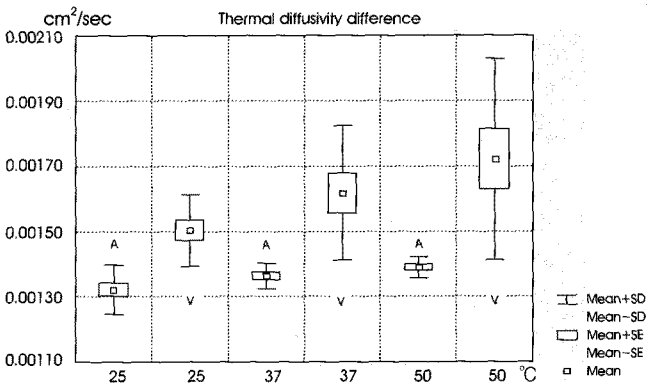


**Fig. 6.** Thermal diffusivity difference between the atrium(a) and the ventricle(v)

structure in the atrium are different in the ventricle. The wall of the atrium is thinner than that of the ventricle. There is less muscle in the atrium, and the atrium is smoother than the ventricle. These difference might make one think the thermal properties of the atrium could be different from those of the ventricle. This experiment results show that there was statistically little difference in the thermal conductivity but the thermal diffusivity was different. There were different experimental protocols between two researches. In measuring the thermal properties of a ventricle, a flesh tissue was been used at every different temperature. Additionally small water bath was used. In measuring the thermal properties of a atrium, the same tissue was used during one sequence, 25℃ to 50℃, and a large water bath and two beakers were used. The same conditions were used as described above, but samples were independent, because the atrium and the ventricle were different.

## V. CONCLUSIONS

Thermal property measurements in swine atrium were presented. Thermal conductivity and diffusivity of swine atrium were measured in vitro within one day post mortem. The experimental data showed there was not only statistically differences in thermal conductivity measured at 25℃ to 37℃, and 25℃ to 50℃, but also thermal conductivity rises with temperature increase. There was not much change between 3 7℃ and 50℃. There was no statistical difference in thermal diffusivity measured at 25℃ to 37℃ and at 37℃ to 50℃, which indicated the thermal diffusivity did not change from 2 5℃ to 37℃ nor from 37℃ to 50℃. Only from 25℃ to 50℃, the thermal diffusivity was shown to change. Atrium thermal conductivity ranged from 5.17 ± 0.12 mW/cm℃ at 25℃ to 5.33 ± 0.08mW/cm℃ at 37℃. Atrium thermal diffusivity ranged from 0.00132 ± 0.00007 $cm^2$/sec at 25℃ to 0.00138 ± 0.0003 $cm^2$/sec at 50℃.

The comparison of the atrium with the ventricle of the swine heart revealed that both the myocardium had the same thermal conductivity. The thermal diffusivity of the atrium was found to be lower than that of the ventricle by about 15%, but the difference was not so significant as to consider in performing the cardiac ablation. In sum, the thermal properties of the atrium in the swine heart need not be taken significantly different from those of the ventricle for the cardiac ablation.

As a future research direction, a noninvasive measurement method needs to be developed. So that, the thermal properties of the myocardium including both the atrium and the ventricle need to be reported for in vivo human tissue.

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