Hearts ablaze!

Radio Frequency Ablation as Treatment for Cardiac Arrhythmia

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Executive Summary:

This project analyzes several of the parameters involved in the use of radiofrequency ablation (RFA) in the treatment of cardiac arrhythmia. Arrhythmia is an irregular beating of the heart that can be caused by improperly timed contractions within the heart, which can, in certain circumstances, be corrected by ablating tissue. One out of every five hundred people is born with an arrhythmia and others acquire the condition through heart disease. For heart attack victims, it is the most common cause of sudden death. RFA is a common way to treat serious arrhythmia cases by cutting the short circuit through the destruction of certain tissues. We used finite element analysis along with prototyping software to determine the duration of treatment, with special attention to the damage caused to surrounding tissue. We found that the optimal parameters for most effective treatment were to administer 30V for 120 seconds – which happens to be the standard method of operation. This destroys the necessary part of the AV node while maintaining the surrounding tissue at relatively normal temperatures.

Introduction:

Arrhythmia is irregular beating of the heart that causes decreased blood flow and oxygen supply to the brain and body, and can be caused by a sort of short circuit within the heart (http://www.acmemphis.com/files/rfafaq.pdf). This causes dizziness, loss of consciousness, damage to the body, increased stress upon the heart, and ultimately shortens the life span of persons with the condition. Individuals with arrhythmia can have their conditions corrected through radio frequency ablation (RFA) of certain parts of the heart, stopping arrhythmia in the heart by interrupting the short circuit (RFA is essentially the thermal destruction of tissue). Typically, the target area is the atrioventricular (AV) node, which is the pacemaker of the heart. RFA is performed by inserting a radio frequency generating tip and a thermocouple through a catheter into the target area. High frequency radio waves are then used to heat up the tissue past 50 degrees Celsius, which permanently denatures proteins and fuses cell membranes, killing the cells, and hopefully restoring the heart to working condition.

Design Objectives:

The main objective of radiofrequency ablation is to destroy target heart tissue (by heating to above 50 degrees Celsius), while maintaining a sufficiently low temperature in the surrounding tissue. GAMBIT was used to create a mesh modeling the region of the AV node and the surrounding heart tissue. FIDAP was then used to model the geometry of the thermal region surrounding the radio frequency ablation tip in order to define the duration of the ablation procedure, and the most appropriate voltage.

"Myocardial injury occurs once a temperature of approximately 50˚C has been reached. Therefore, the optimal goal of RF ablation is to be able to elevate the base tissue temperature of 37˚C uniformly to a temperature above 50˚C. However, the tissue

temperature should be kept below 100˚C. At approximately 100˚C, charring, desiccation, boiling, and popping take place which can modify the electrical conductivity of blood and tissue."[8] Thus, the object of RF ablation is to disable the AV node (pink) by destroying it by heating it to a temperature between 50 and 100 °C, while maintaining a temperature level below 50 °C in the surrounding tissue.

Schematic:

Figure one shows the area of the AV node and surrounding heart tissue. We meshed in Gambit only the upper half of this diagram in our mesh, as the geometry is axi-symmetric.

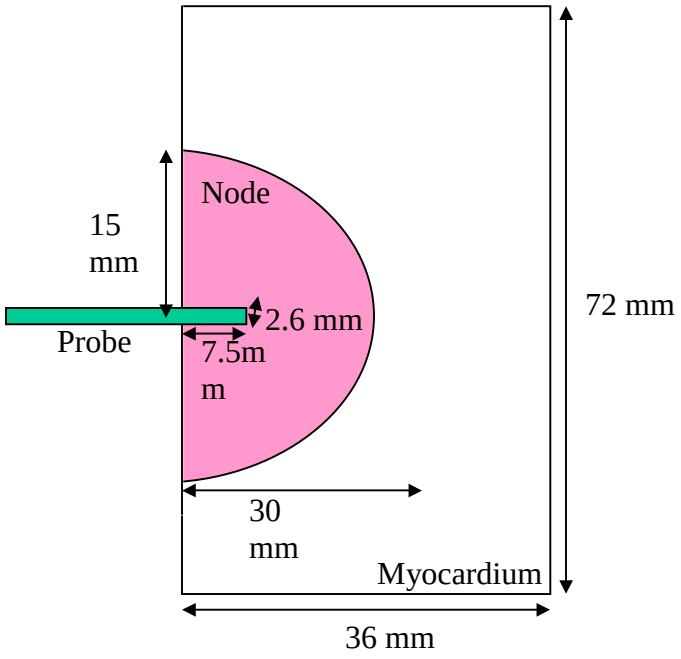

Figure 1: Schematic and dimensions of area to be destroyed.

Results and Discussion:

The problem was simulated by applying a constant voltage of 30 V to the ablation electrode for 120 seconds. “An electric current with a frequency between 300 kHz and 1 MHz is applied to the metal electrode that is in contact with the arrhythmic substrate.” [2]

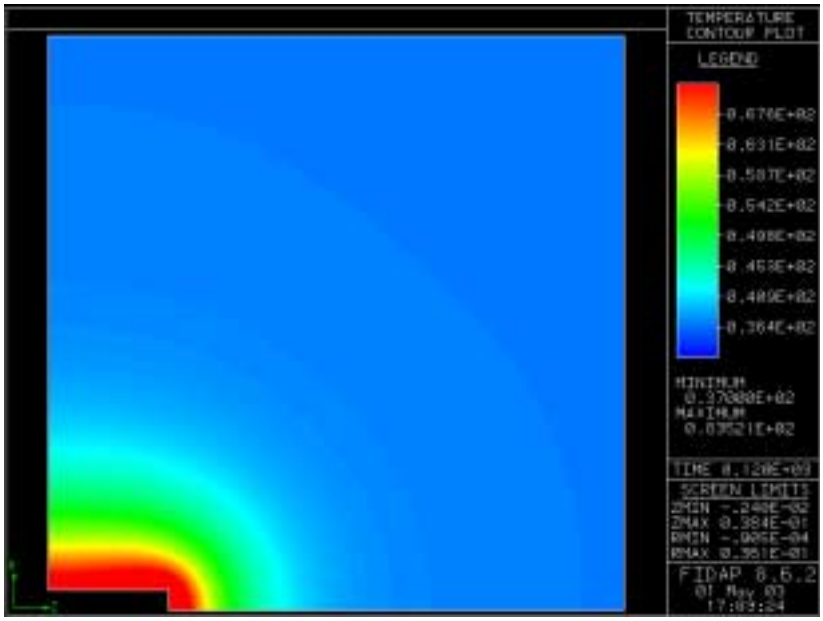

Figure 2: Temperature contour plot of 30V heating after 120 seconds.

“Typical ablation catheters… create lesions approximately 5 to 6 mm in diameter and 2 to 3 mm deep.”[5] As can be seen in figure 2, the AV node reaches temperatures of above 50°C in over 50% of the node to be destroyed, while remaining far under the critical 100 °C. The surrounding tissues also remain relatively close to 37 °C, demonstrating a successful procedure.

The temperature can be seen over time in the following plots. In figure three, we see the rise in temperature over time at node 12, which is near the edge of the zone of destruction. It successfully reaches a temperature of above 50 degrees C at the final time of 2 minutes.

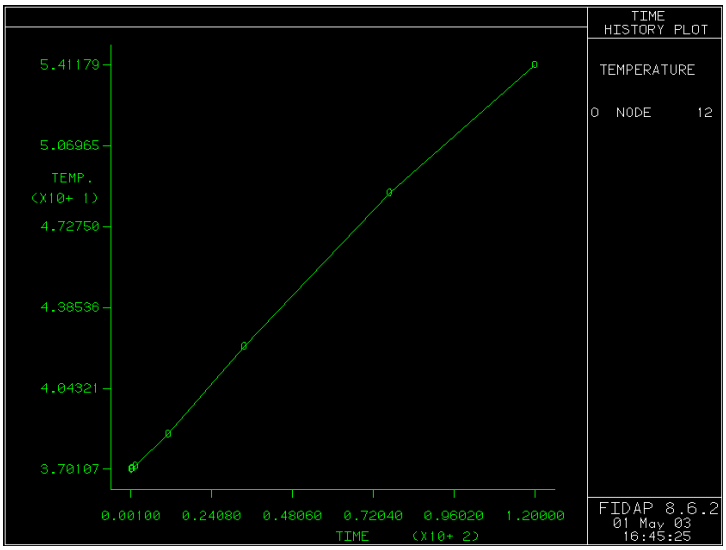

Figure 3: Temperature at node 12 over 120 second period.

In figure four, it is shown that the surrounding tissue successfully maintains a temperature that is close to (within one degree Celsius) normal body temperature by showing the rise in temperature of node 21 over time.

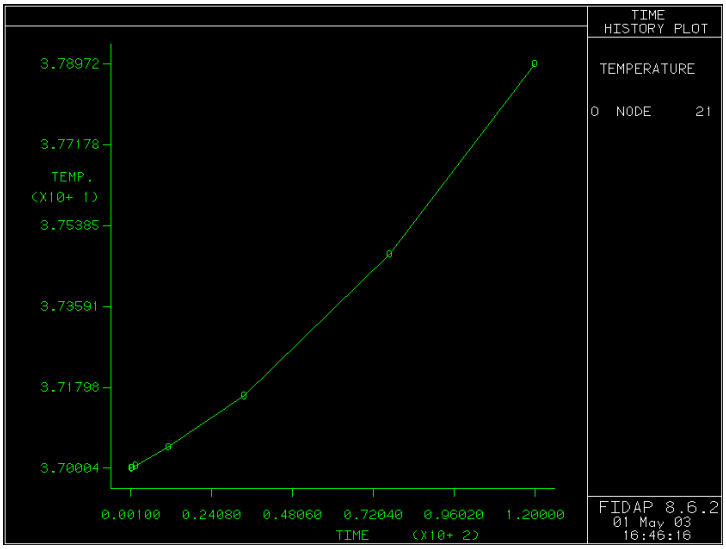

Figure 4: Temperature at node 21 over 120 second period.

Figure five shows that cell death heating boundary becomes rounded as is moves outward, which is convenient because the AV node that we wish to destroy is rounded. The first contour (nearest to the probe) is the boundary of 50 degree Celsius heating after 30 seconds have passed. Each progressive contour shows the movement over time of the heating front. The fifty degree boundary is important because it defines our kill zone.

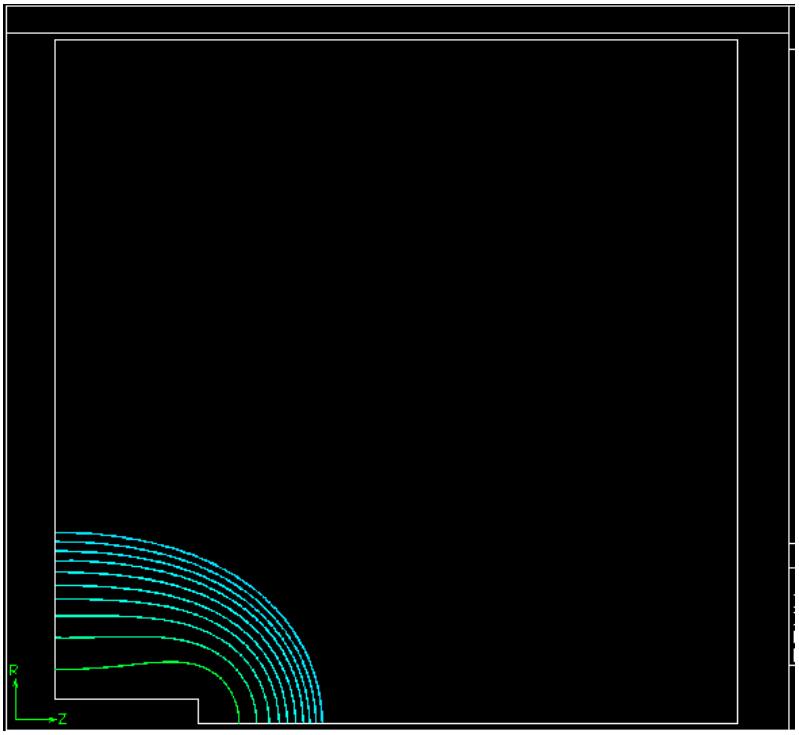

Figure 5: Progression of the fifty degree contour line heating boundary at 30 second intervals using 30V.

Figure six shows that greater voltage results in faster heating. Three different voltages are plotted: 20, 25, and 30V. These are the voltages that are typically used in practice to perform RFA. We found that using greater voltages resulted in a crisper boundary. This means that fewer cells in the tissue immediately surrounding the kill boundary reached higher temperatures. The other factor that had to be considered was the possibility of reaching a temperature of greater than 100 degrees Celsius in the tissue adjacent to the probe before the intended kill zone was destroyed. This resulted in an upper voltage limit for the probe. At 30V, this upper boundary temperature was not reached within 120 seconds.

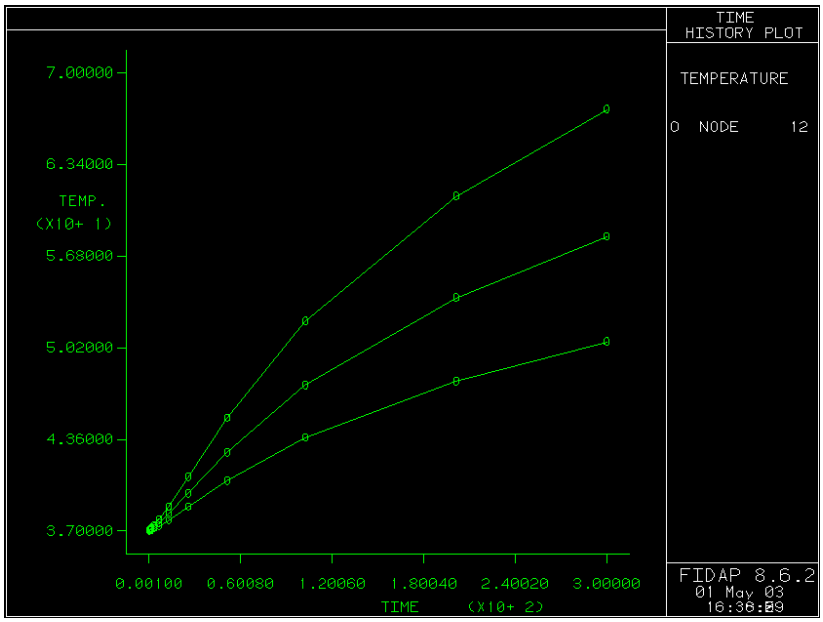

Figure 6: Heating of node 12 over time at different voltages.

Sensitivity Analysis:

In order to determine the effect of the various properties on the solution, the values of density, specific heat, and electrical conductivity were varied by ±10% from the accepted value and temperatures at points, both inside the AV node and in the surrounding tissue, were measured. The effect of using constant vs. varying thermal conductivity was also examined.

	Property Value	Node Temp (°C)	Tissue Temp (°C)
Density (kg/m^3)	1080	53.6	37.95
	1200	54.1	37.9
	1320	54.5	37.85
Specific heat (J/kgK)	2880	55.45	38.06
	3200	54.1	37.9
	3520	52.93	37.78
Electrical conductivity (S/m)	0.1998	52.42	37.81
	0.222	54.1	37.9
	0.2442	55.81	37.99
Thermal conductivity (W/mK)	varying with temp	54.1	37.9
	0.550	54.03	37.9

Figure 7: Data obtained for sensitivity analysis by gauging node temperature.

There was little variation in the tissue temperature, but the changes in nodal temperatures can be seen below. The first bar represents a 10% decrease, the second bar is the normal property value, and the third bar shows a 10% increase for density, specific heat, and

electrical conductivity. Each of the numbers above the bars displays the percentage change from the normal value. The property that was most affected by a 10% change in value was electrical conductivity, which changed more than 3%. The thermal conductivity did not vary significantly if using a constant value instead of the temperature-dependent value.

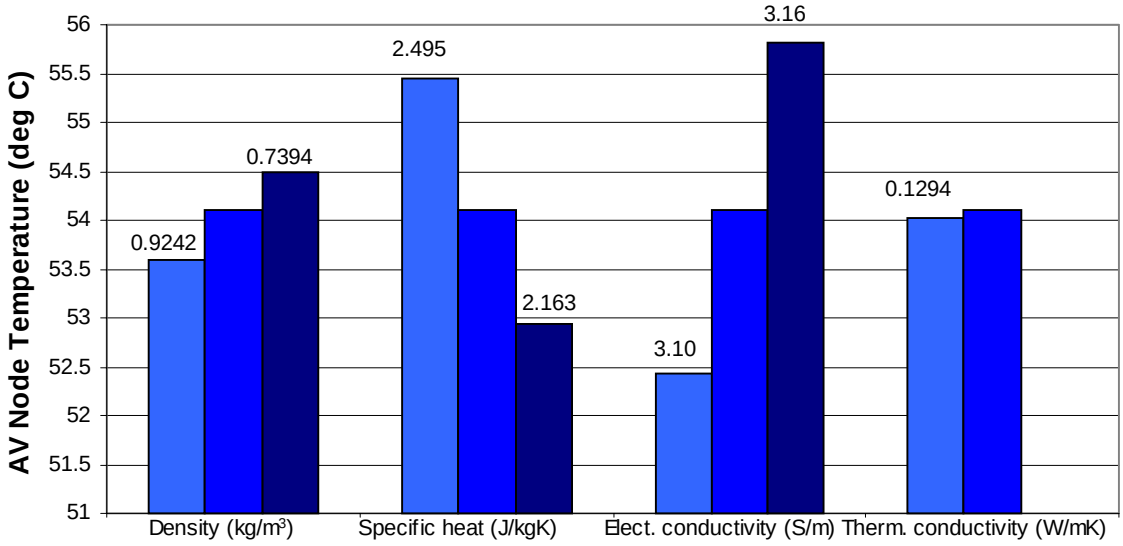

Figure 8: Sensitivity of AV node temperature to different property values.

Conclusions and Design Recommendations:

Using the finite element analysis program FIDAP, we found the current methodology for administration of RFA to be acceptable in reaching its stated objectives. Higher voltages or longer periods of ablation result in more charring (temperature of tissue adjacent to the probe being in excess of 100° Celsius). Lower voltages or shorter periods of ablation resulted in a greater amounts of tissue being heated to dangerously high levels before the appropriate percentage of the node was destroyed. The standard, optimal method was found to be administration of 30V through an electrode of the size typically used for 120 seconds.

Appendix A:

Geometry:

Please refer to the schematic shown - figure one.

The following selections were chosen to define the problem definition: axi-symmetric geometry, transient simulation, no-momentum equation, and energy temperature dependence. Axi-symmetric geometry was used because the probe and node were symmetric about the x-and y-axes. A transient solution to the energy equation was sought because the temperature of the node and the surrounding tissue change with time. Finally, there is no relevant fluid movement, so the momentum equation was not solved.

Governing Equations:

Bio-heat Equation

$$\rho c \frac{\partial T}{\partial t} = \nabla * k \nabla T + JE - h_{bl}(T - T_{bl}) - Q_{el} + Q_m$$

Where:

$$h_{bl} = \rho_{bl} c_{bl} w_{bl}$$

When blood flow and respiration effects were considered negligible compared to the rapid voltage heating taking place, the following equation was derived:

$$\rho c \frac{\partial T}{\partial t} = \nabla * k \nabla T + JE$$

LaPlace Equation - Used compute the electric field and heating intensity.

$$\nabla \cdot \sigma \nabla V = 0$$

Where:

$$E = -\nabla V \qquad \textit{and} \quad J = E\sigma$$

Species Equation

$$\frac{\partial c}{\partial t} = D\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial c}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 c}{\partial \theta^2}\right) + R$$

This is the axi-symmetric form of the species equation, where the diffusivity term is calculated based on the σ value and concentration is really as a function of radius has to do with the voltage equation written above, as discussed in the

properties section. The "R" value is set equal to zero because there is no voltage generation within the tissue.

Boundary Conditions:

1. T always = 37°C at outermost boundary of the equation.
2. No heat flux at the probe boundaries.
3. V = 0 around the edges.
4. V = 30V (constant) at probe boundaries.

Initial Conditions:

T = 37°C when t=0

Properties:

	Density *[kg/m^3]*	*Specific Heat* *[J/kg * K]*	*k* *[Watts/m * K]*	σ *[S/m]*
Cardiac Muscle	1200	3200	.550	0.222

Figure 9: Approximate property values (with constant k) [6]

T_{bl} = 37˚C (assumed to be constant due to high flow in the heart chamber)
Q_m (energy generated by metabolic process) = 0 (negligible)
Q_{el} (heat exchanged between the electrode and the tissue) = 0 (negligible)

"Assume that cardiac tissue is purely resistive at the frequencies from 10 kHz to 500 kHz and the reactive term is negligible"[2]. Thus, temperature-dependent thermal conductivity of the cardiac tissue [6]:

$$k = k_0 + k_1 T = 0.4925 W/mK + (0.001195 W/mK°C) \cdot T$$

The electrical conductivity was not entered directly, but used to enter the value of diffusivity, which was calculated as follows:

$$D = \frac{1}{2\rho}\sigma = 0.0000925$$

Appendix B:

(a) PROBLEM statement keywords

Geometry type	Axi-symmetric	The system is symmetric across the axis, so only one calculation is needed to understand the results.
Flow regime	Incompressible	The contents are incompressible.
Simulation type	Transient	The results depend on time.
Flow type	Laminar	The flow is laminar.
Convective term	Linear	There is no convection.
Fluid type	Newtonian	The system behaves in a Newtonian manner.
Momentum equation	No momentum	There is no momentum in the tissue.
Temperature dependence	Energy	The energy term accounts for the thermal conduction.
Surface type	Fixed	The surface is fixed.
Structural solver	No structural	There is no structural solver.
Elasticity remeshing	No remeshing	There is no remeshing.
Number of phases	Single phase	There is only matter of a single phase.
Species dependence	Species = 1	There is one species.

(b) SOLUTION statement keywords

Solution method	Steady state = 10	This sets the program to solve a steady state problem with a maximum of 10 iterations for any one time step.
Relaxation factor	ACCF = 0	

(c) TIMEINTEGRATION statement keywords

Time integration	Backward	This specifies the time integration method for a transient analysis.
No. time steps	Nsteps = 1000	The maximum number of discrete time integration steps to be calculated is 1000.
Starting time	Tstart = 0	The starting time is 0.
Ending time	Tend = 120	The ending time is 120s.
Time increment	Dt = 0.1	The time increment is 0.1s.
Time stepping algorithm	Variable = 0.1	The time increment is variable and determined by control of the local time truncation error via the tolerance level of 0.1.
Max Increase Factor	Incmax = 10.0	This is the larges possible increase factor for the time step.

Mesh:

The RF catheter is seen in the lower left corner. Heat emanates from there, causing more change in that area. Thus, there is a higher density of nodes in that region:

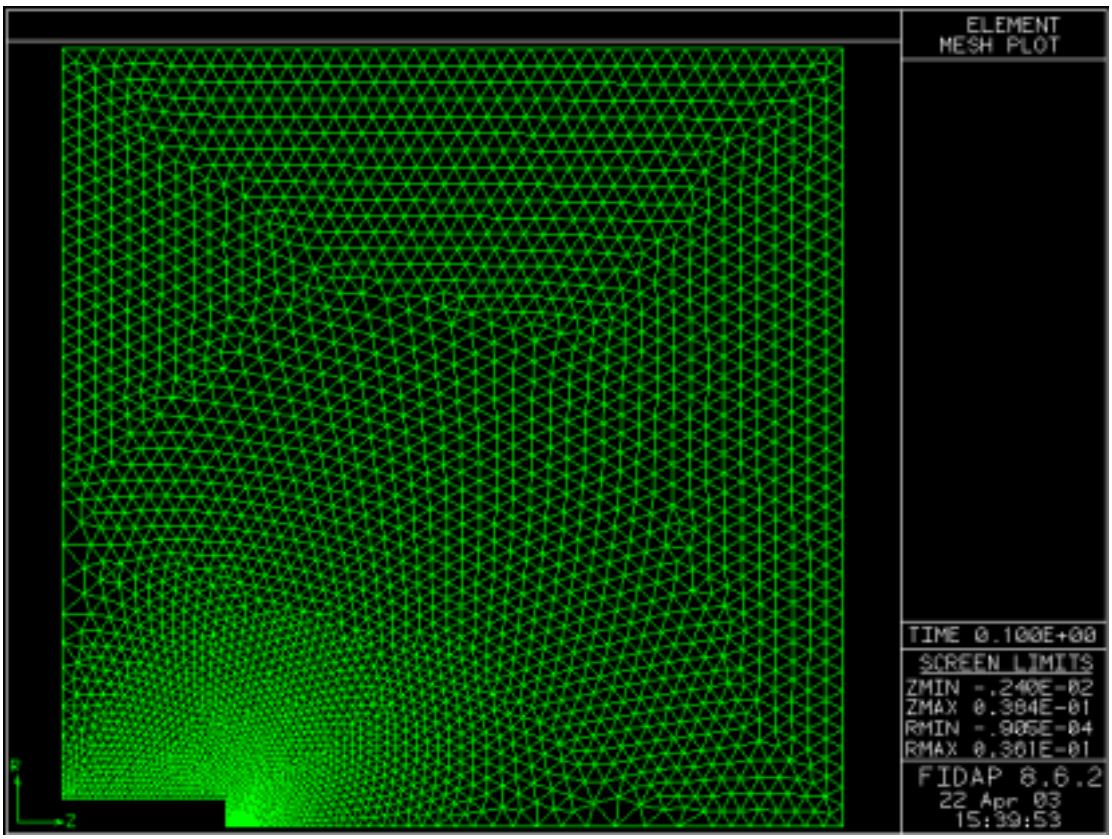

Figure 10: Appearance of final mesh. Note the higher density near the probe, where temperature changes are greater and more rapid.

Convergence analysis:

Five different meshes were created with varying number of nodes in both the region of the AV node itself and the surrounding heart tissue.

	Number of Nodes in Mesh			Temperature of Region (°C)	
	AV Node	*Heart Tissue*	*Total*	*SA Node*	*Heart Tissue*
mesh 1	2385	2185	4570	55.56	38.05
mesh 2	1564	1530	3094	52.96	37.955
mesh 3	1564	1001	2565	52.95	37.7
mesh 4	3226	2879	6105	54.12	37.89
mesh 5	5088	3704	8792	53.84	37.97

Figure 11: Data collected for convergence analysis.

The number of meshed nodes in the area of the AV node was plotted against the temperature found at a certain point in that region, and the number of meshed nodes in the area of the surrounding heart tissue was plotted vs. the temperature. As there is little change in temperature expected in the surrounding heart tissue, the number of nodes in that region should not matter very much. This is supported by the lack of temperature variation in the plot. There is a large change in temperature in the area of the AV node, and because burning causes a rapid temperature change, there is a large density of elements present. The nodal dependence appears to taper off after the point at 3226 nodes. Based on this evidence, our group used mesh 4 for our computations.

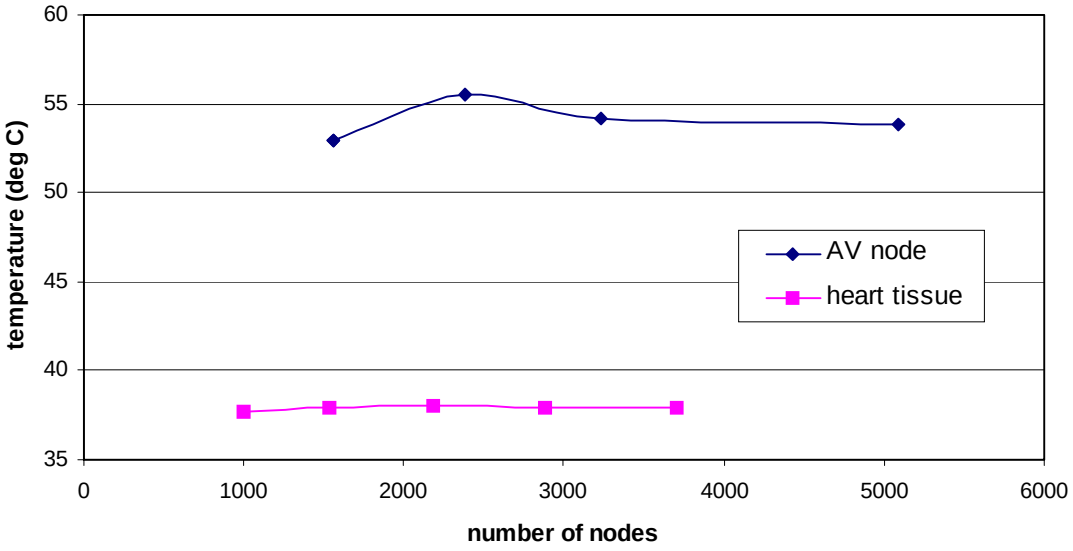

Figure 12: Mesh convergence data.

References:

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[2] Cao, H., Speidel, M.A., Tsai, J., Van Lysel, M.S., Vorperian, V.R., and Webster, J.G. 2002, June. "FEM analysis of predicting electrode-myocardium contact from rf cardiac catheter ablation system impedance." *IEEE Transactions on Biomedical Engineering, 49*, 520-525.

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[5] Morady, F. "Radio-frequency ablation as treatment for cardiac arrhythmias." Retrieved April 21, 2003 from http://www.ecu.edu/intmedresidency/CurrentResidents/Review Articles/second collection/Radio-Frequency Ablation as Treatment for Cardiac Arrhythmias.pdf

[6] Tungjitkusolmun, S., Cao, H., Tsai, J., and Webster, J.G. 1997, Oct. 30 – Nov. 2. "Using ANSYS for three-dimensional electrical-thermal models for radio-frequency catheter ablation." *Proceedings – 19th International Conference*. IEEE/EMBS, Chicago.

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[8] Tungjitkusolmun, S., Woo, E. J., Cao, H., Tsai, J., Vorperian, V.R., and Webster, J.G. 2000, January. "Finite element analyses of uniform current density electrodes for radio-frequency cardiac ablation." *IEEE Transactions on Biomedical Engineering, 47*, 32-38.