BEE 453 : COMPUTER AIDED ENGINEERING

Project Report

Radiofrequency Ablation to kill Kidney Tumors

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Executive Summary and Motivation

Radiofrequency ablation is a technique to destroy tissue cells by heating them above 46^0C. This method is specifically used in treating tumors smaller than 5 cm in diameter by placing the heated probe within the dysfunctional tissue mass. Depending on the size and shape of the tumor, the ideal time of treatment, voltage, and shape of probe required to eliminate the cells is decided. This study tested a spherical tumor with a 2 cm diameter to determine the best probe shape, voltage, and time of treatment to destroy cancerous cells while keeping surrounding tissue unaffected. Our results indicated that a lower voltage (0.27 volts) and a longer period of time (700 seconds) yielded the best results when using a T-shaped probe. These results account for the diffusion of the heat within the tumor cells while minimizing the damage to the surrounding tissue. Sensitivity analysis indicated that specific heat and tissue density had very small impact on the temperature profile.

Introduction

Cancers of the kidney are a difficult medical problem because frequently they can not be removed surgically. Chemotherapy is not always effective, and there is a great need for other methods to try to reduce or eradicate these tumors.

Radiofrequency ablation (RFA) is a method developed to treat kidney cancers without surgery or chemotherapy. Like any cancer treatment, it is not the right choice for everyone, and is not always effective. However, it is becoming much more useful and popular as a good way to destroy many tumors of the kidney.

Radiofrequency ablation kills kidney tumors with heat. The entire treatment is done by the Radiologist while seeing the liver tumor on an ultrasound or CAT scan picture. A thin needle (an electrode) is placed through the skin directly into the liver tumor. The electrode is connected to a generator that sends radio waves directly to the tip of the needle. This wave energy creates heat in the electrode inside the tumor, and spreads out to destroy the entire affected area. There is a shaft that insulates a part of the probe so that the heat can be directed to the tumor. The probe has to heat the tumor up to $46^{o}C$ to effectively kill it. The treated tumor begins to die (necrosis) immediately, and the change can be seen right away on the CAT scan. If there are other tumors to be treated, they can usually be done at the same time. After 10 to 30 minutes of contact with the tumor, the radiofrequency energy kills a 2.5- to 5-cm sphere.

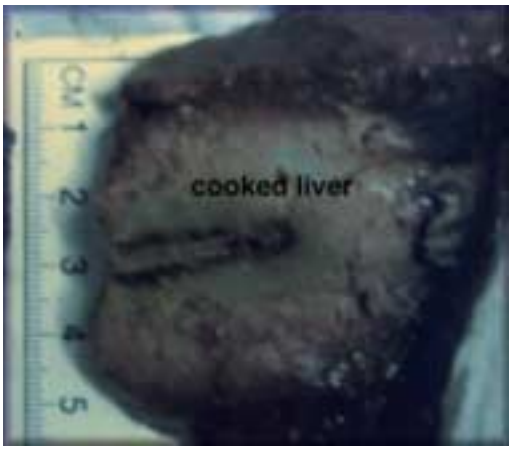

Fig. 1 - Gross in vitro liver specimen showing heated, dead liver in the middle with uncooked normal liver on the outside. Note the sharp predictable margin between treated and untreated. The dark line in the middle is the needle tract. (***Ref. – www.NIH.gov)***

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(a) (b)

Fig 2. – (a) Pre-treatment CT scan of kidney tumor; (b) Post-treatment CT scan of kidney tumor showing complete treatment, seen as eradication of contrast enhancement (***Ref. – www.NIH.gov)***

A small needle with an active tip that is water-cooled to prevent charring or overcooking, and a coaxial needle system with inner hot hooks deployed once inside the tumor.

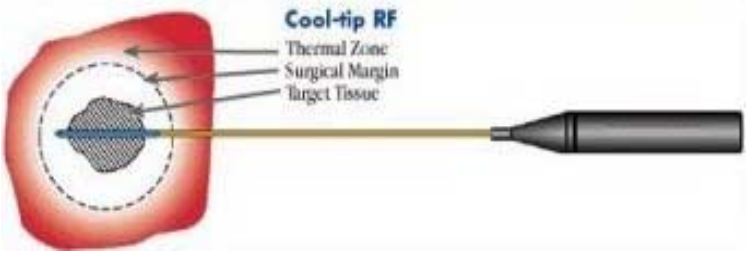


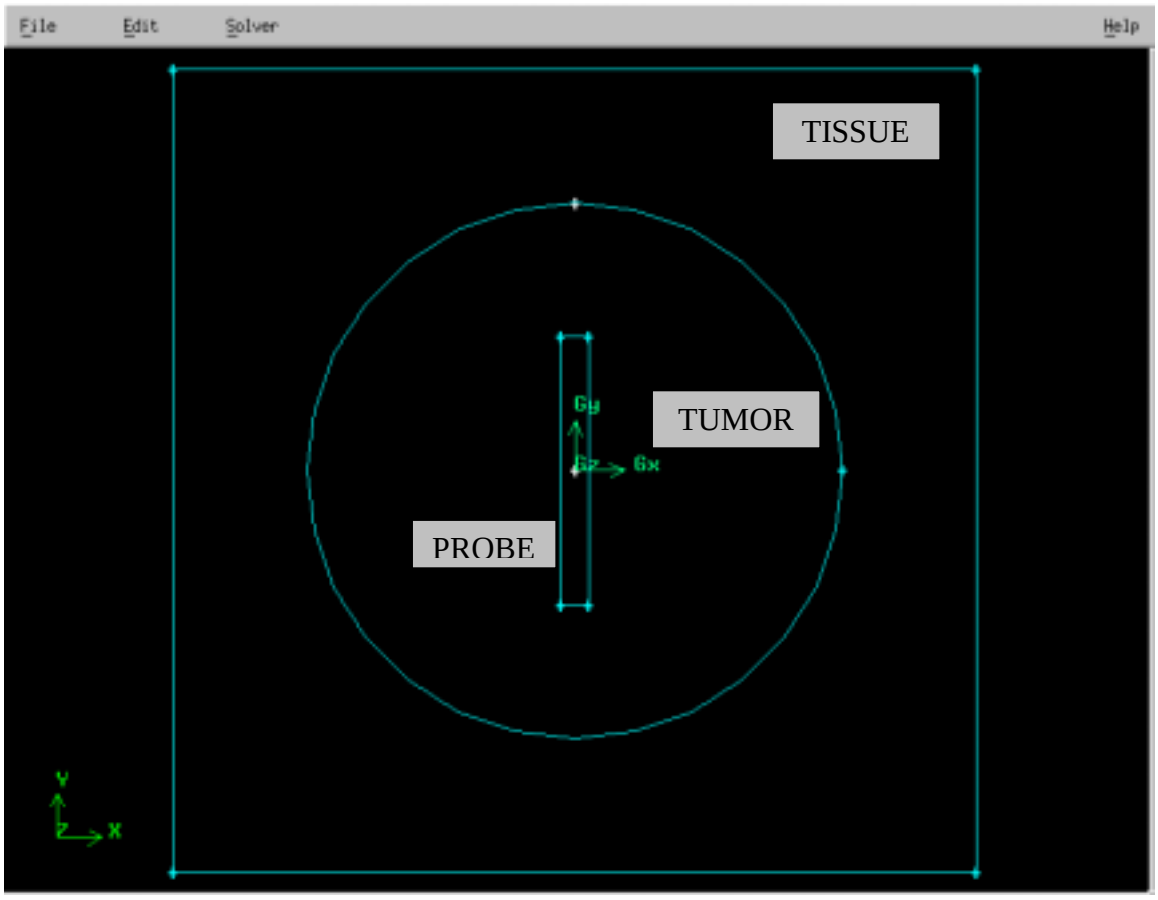
Fig. 3 – The Tip used in the Radio Frequency Ablation System (***Ref. – www.NIH.gov)***

Geometry

Following are the geometries that we assume for various entities in the problem –

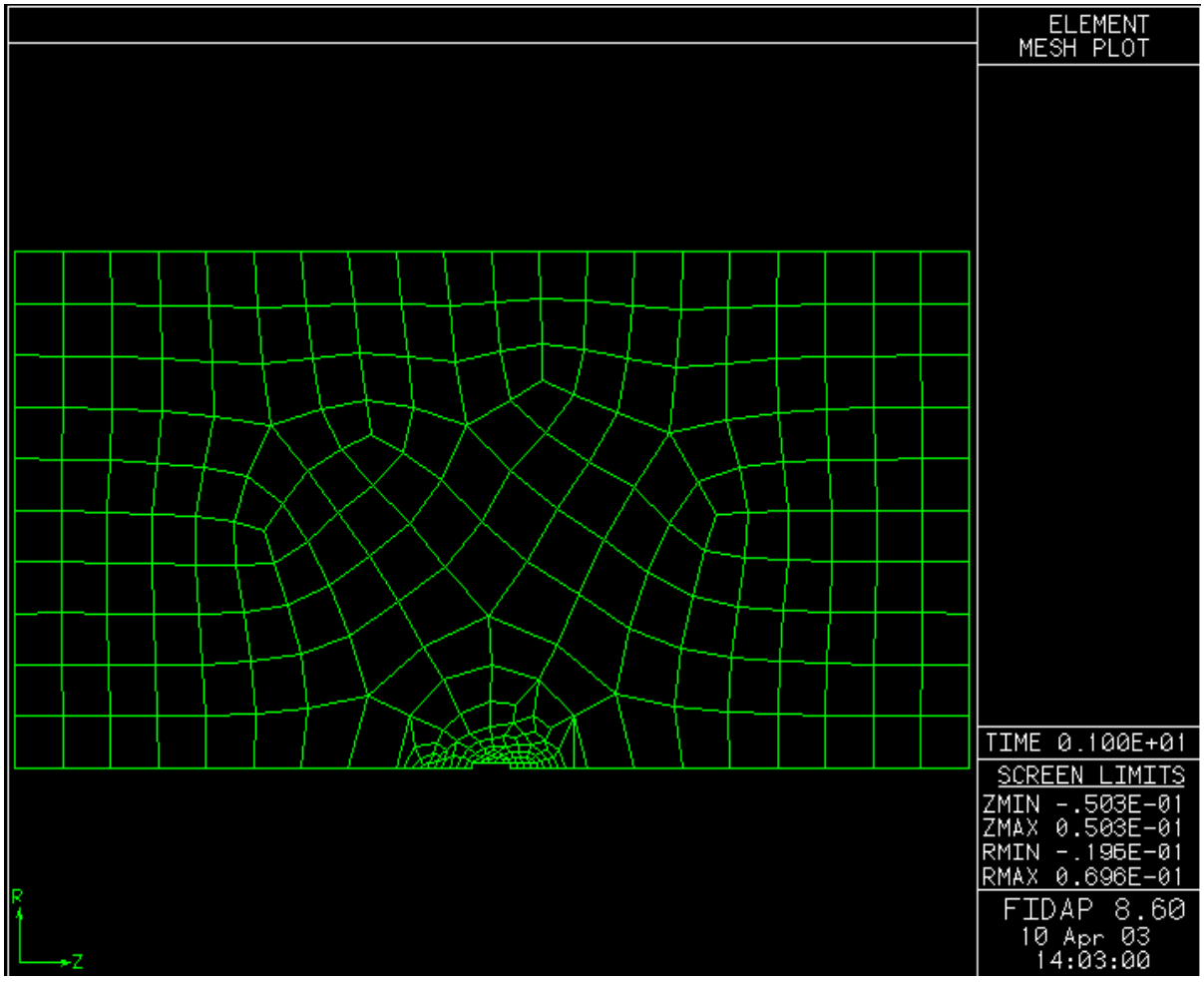
- Tumor - We assume a spherical geometry for the tumor so in 2-D it has a circular shape. This conversion from 3-D to 2-D is justified because of the symmetry of the problem. So while analyzing this problem in GAMBIT we assume an axi-symmetric geometry and analyze only half of the complete problem as the other half will behave in exactly the same way and this will help us in saving some unnecessary computation time.
- Tissue – We assume the tissue surrounding the spherical tumor to be in the form of a cubical lump surrounding the tumor so that in 2-D it looks like a square surrounding the circular tumor. The size of this tissue is just enough to take care of all the temperature variations. This means we randomly select a large size of the tumor initially and check out the temperature variation at the boundary of the square shaped tissue, if we still have large temperature variations, increase the size of the tissue, if it is too large so that the temperature variation becomes insignificant, we reduce its size.
- Probe – We assume a cylindrical probe inserted into the tumor so that it just reaches the center of the tumor. It is insulated from the top and in 2-D it looks like a rectangle inserted into a circle (tumor). We also used an L shaped probe (shown below) as a second geometry to study the voltage and temperature distributions of a more complicated geometry that is similar to the probes used in industry.

The Schematic in GAMBIT



The Meshed Geometry

The following is the mesh used for our calculations – smaller elements around the probe with bigger ones farther in the tissue to save computational time as there is not much variation at large distances from the probe



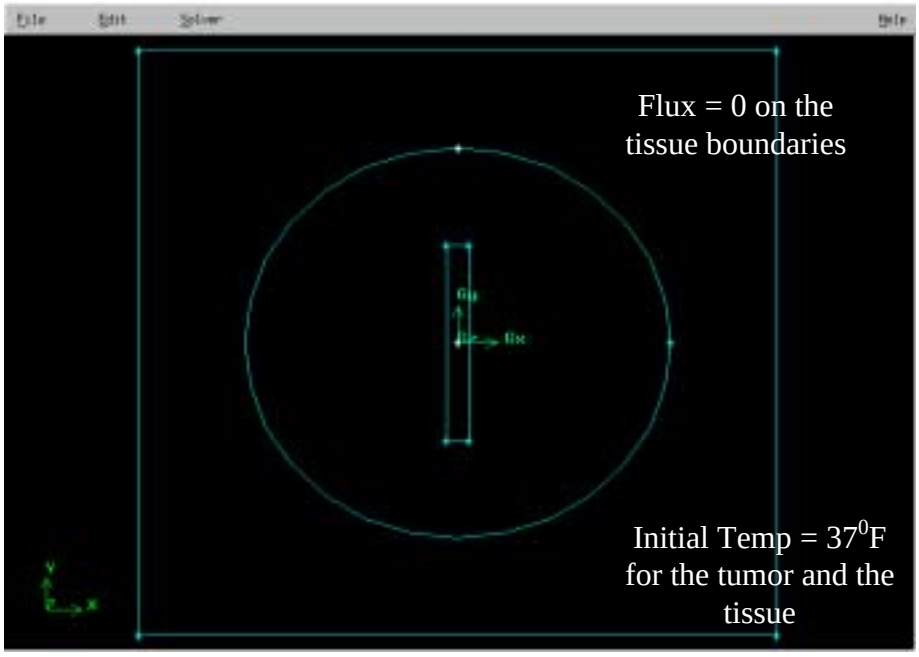
(This is the original mesh)

Governing Equations and Boundary Conditions

We used the energy equation as we don't have any convection or momentum. So for no convection condition (v's all zero) and Axis-symmetric case (no z dependence) the equation gets simplified to

$$\rho C_p \left(\frac{\partial T}{\partial t} \right) = k \left[\frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right] + Q$$

The boundary conditions used are indicated in the following figure –



Species Equation *(Voltage Equation)*

For axis-symmetric case, it simplifies to -

$$\frac{\partial C}{\partial t} = D\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial C}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 C}{\partial \theta^2}\right]$$

The voltage is equal to zero at the edges of the kidney

So the source term in the first equation can then be used as –

$$Q = \frac{\sigma}{2}E^2$$

Properties

1. Thermal Conductivity of the tissue and tumor – k = 0.54 W/mK
2. Density of the tissue material - $\rho = 1.05 \times 10^{+3} Kg/m^3$
3. Specific heat for the tissue and the tumor - $C_p = 3.9 kJ/kgK$
4. Diffusivity – D = σ/2=0.54/2=0.27

These properties were taken from:

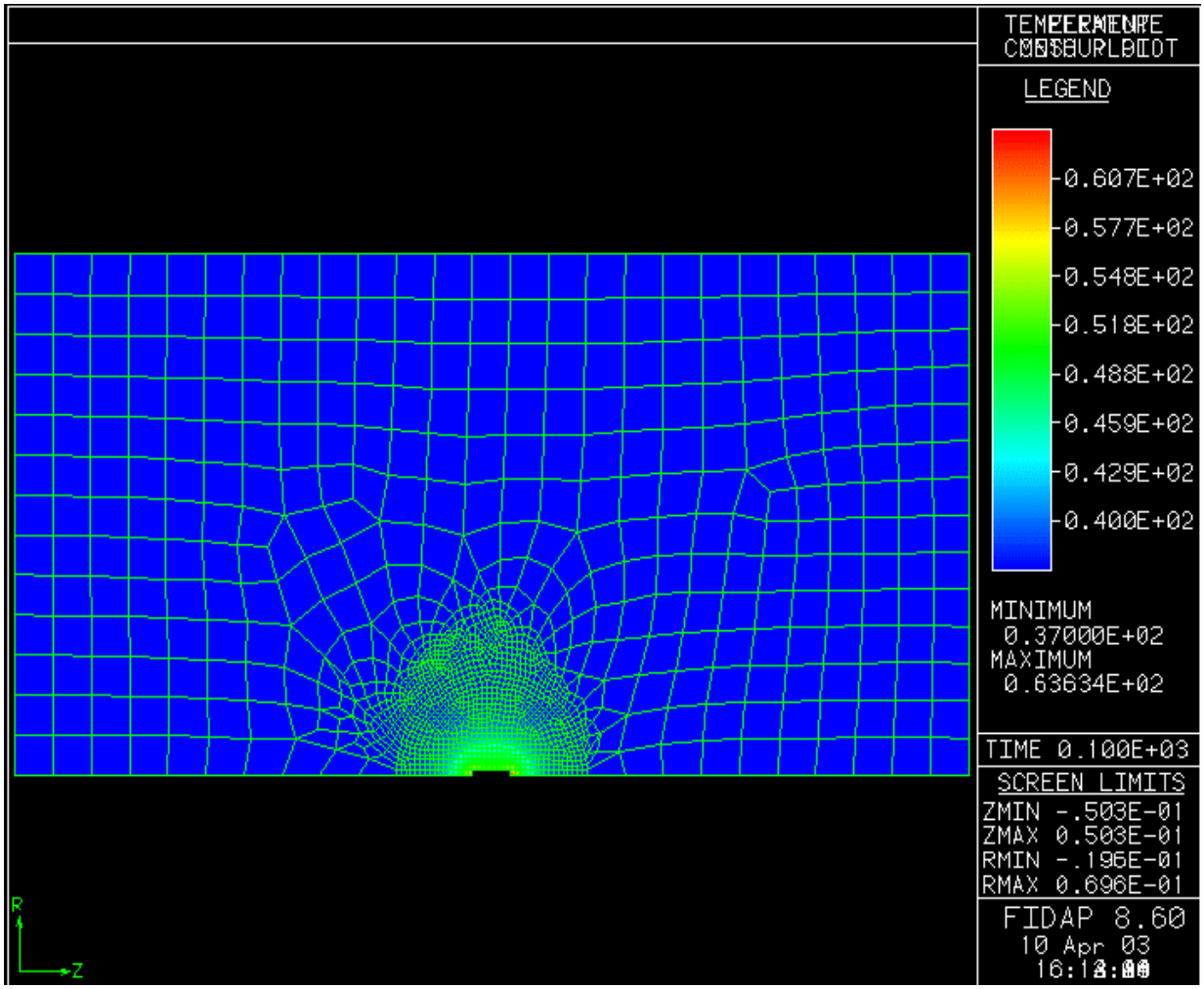
Andersson-Engals, S. Bioheat equation. Referenced on April 16, 2003:

http://kurslab-atom.fysik.lth.se/FED4Medopt/bioheatequation.pdf

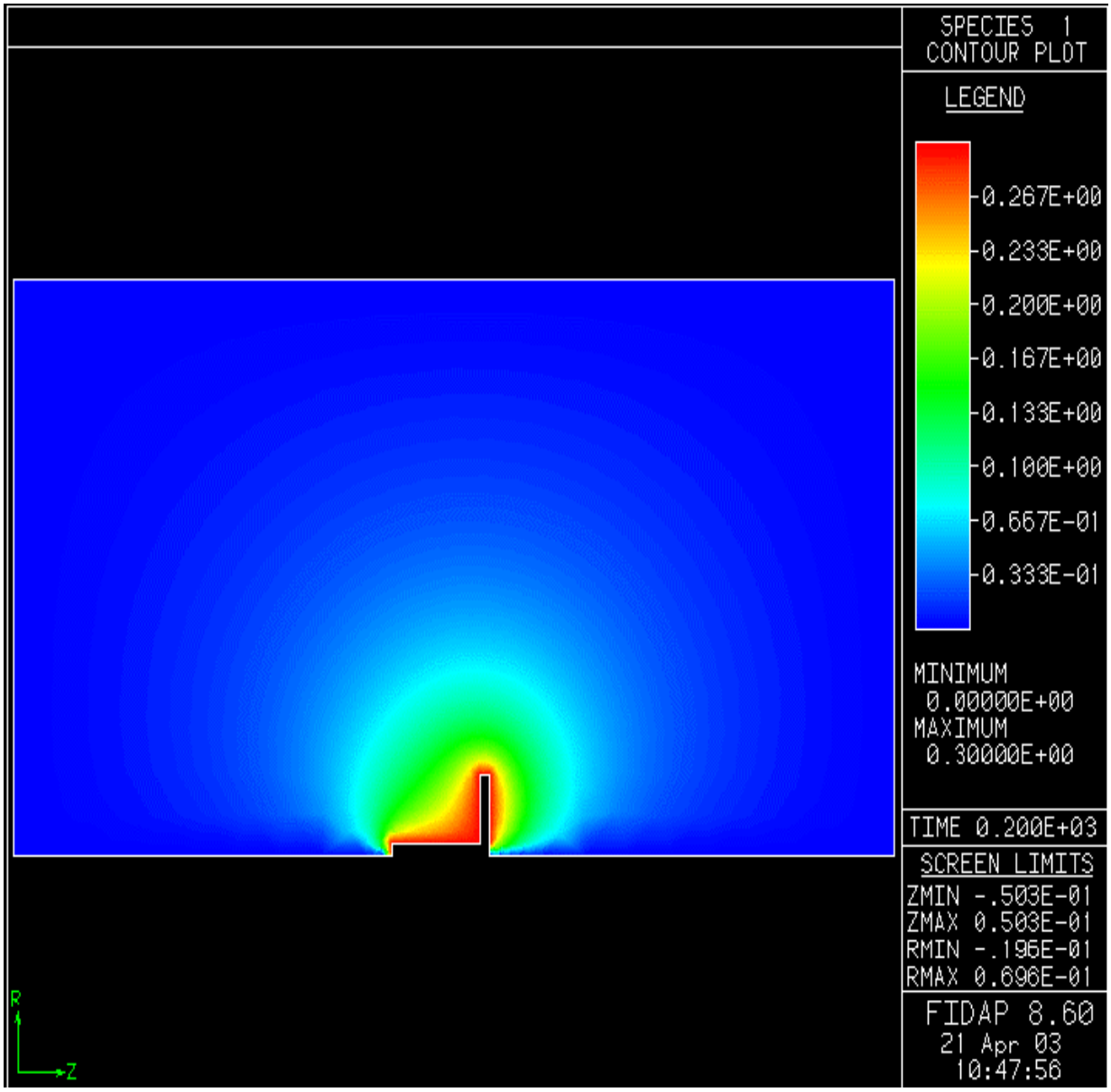
Results and Discussion

| Effect of the change in size and shape of the probes

a) Voltage Plot for the tumor using original probe

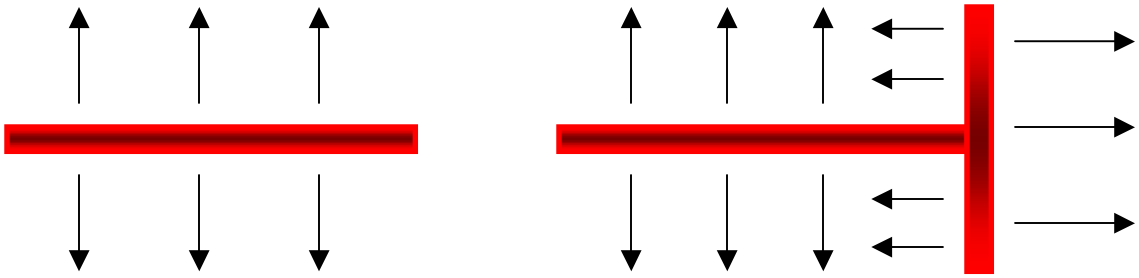


b). <u>Voltage Plot for the tumor using revised probe</u>



Discussion

So in the above sensitivity analysis we tried to analyze the impact of the change in shape and size of the probe on the temperature distribution. Two kinds of probes that we used in the analysis are -



(a) **(b)**

So probe (a) is the original cylindrical probe radiating energy from the outer periphery. So in this case the temperature distribution is as expected, i.e., symmetrical about the probe. However in actual surgery, it is the T-shaped probe as shown figure (b), is used. So in this case the temperature profile shows to be skewed towards the T of the probe. This kind of probe will show a higher temperature towards the T and will protect the holding instrument of the probe from reaching high temperatures while simultaneously reaching higher temperatures at the opposite end.

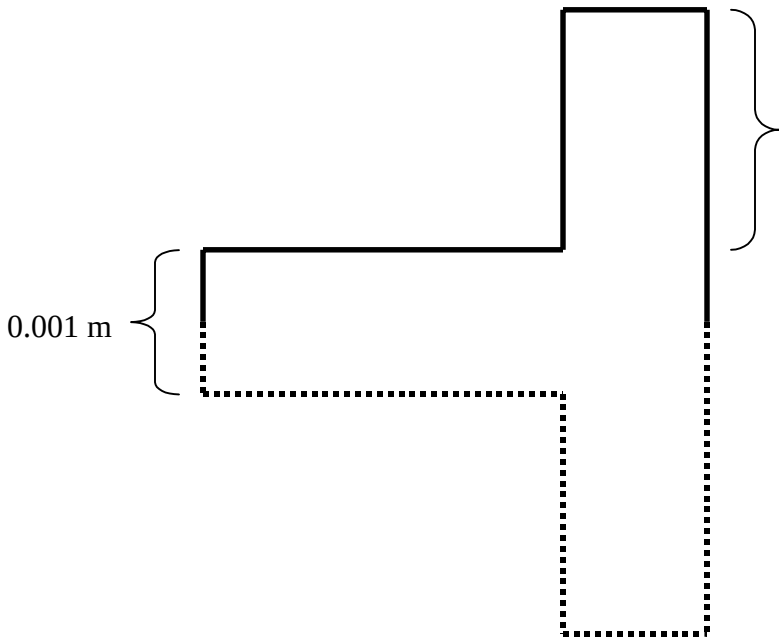
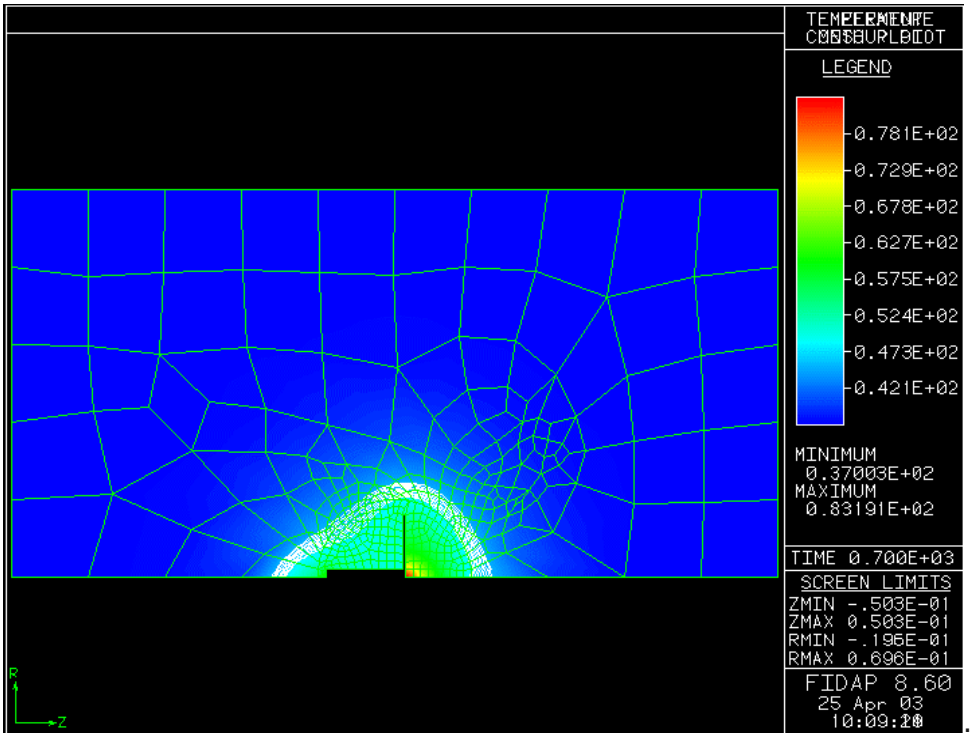
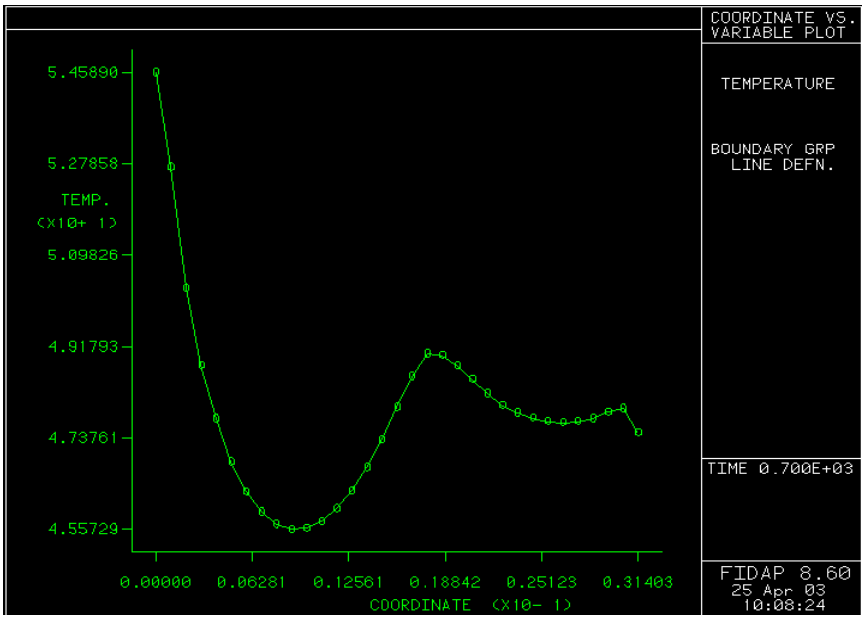


Fig. 5 The Size and Dimensions of a Typical T-Probe

|| Optimum solution for the shape and size of the Probe



Temperature Profile Along Tumor Boundary

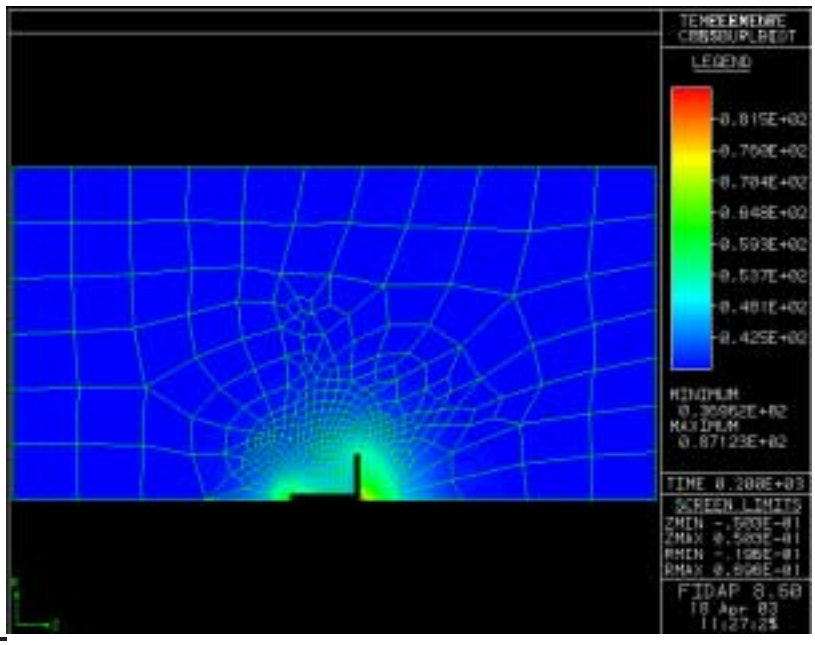


Discussion

So the two figures shown above clearly show how the temperature varies along the boundary of the tumor. An optimum solution would be the one that results in a temperature of just about 45^0C at the boundary of the tumor and higher inside, so that in this way the tumor can be burnt completely while at the same time not harming the healthy tissue; as just outside the tumor the temperature will be less than 45^0C. The variation of the temperature with the boundary (graph 2) shows that the temperature is consistently higher than 45^0C inside the tumor. The U-shaped of the graph is due to the T-shaped probe. So this shape helps in maintaining the lowest temperature at the center of the boundary (but still keeping it higher than the required 45^0C) thereby minimizing the temperature of the healthy tissue at the center. In order to compare this, we present a solution where the temperature inside the tumor remains less than 45^0C.

An Ineffective Solution

Voltage=0.3V at Time=200 seconds *(using mesh 1 from App.)*

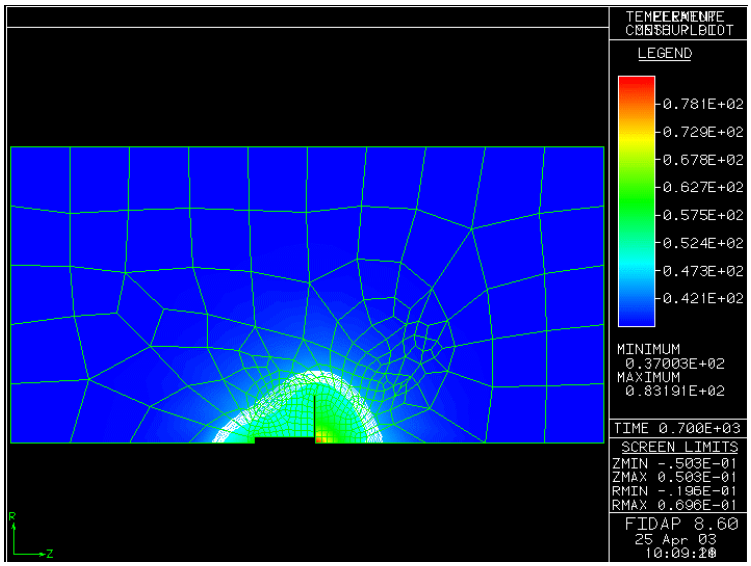


Sensitivity Analysis

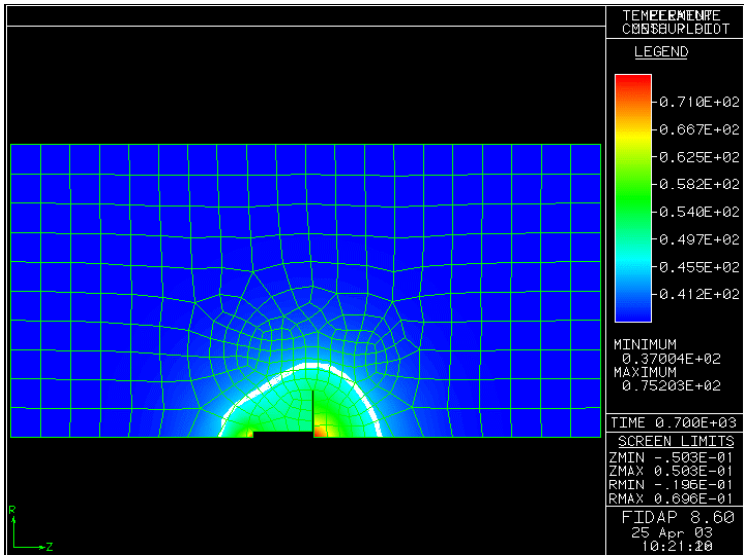
I. Analysis for Various Meshes for the T-Shaped Probe

Plot of voltage at 0.27V for 700 seconds
The white lines represent the 45-46C boundary

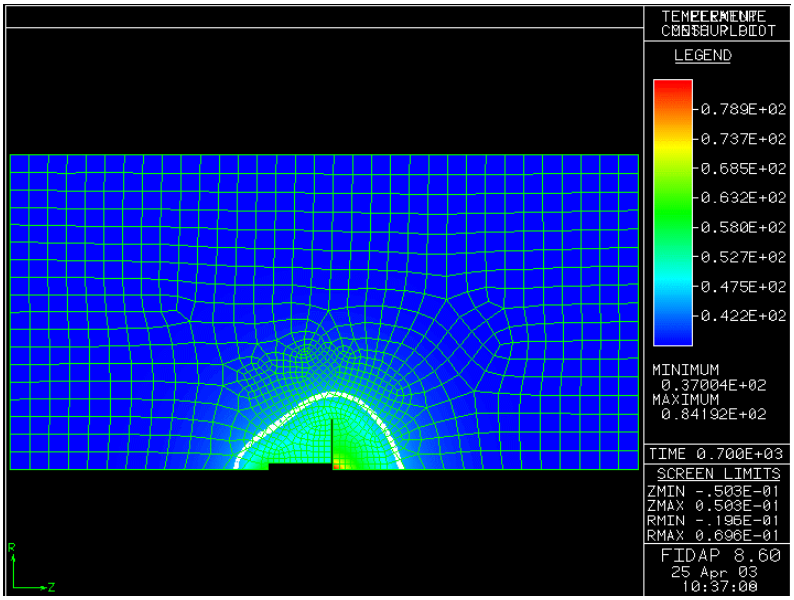
(a) Using MESH 1 *(from Appendix)*



(b) Using MESH 2 *(from Appendix)*

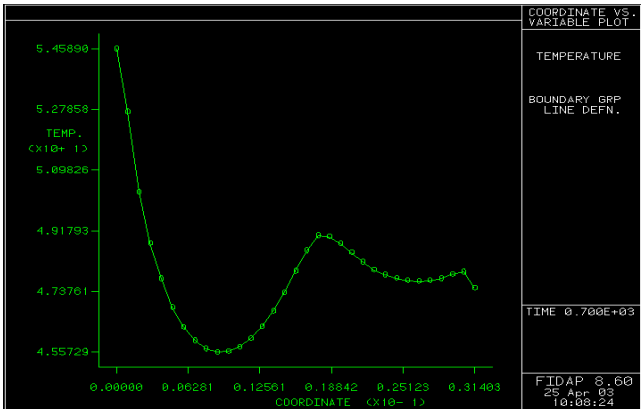


(c) Using MESH 3 *(from Appendix)*

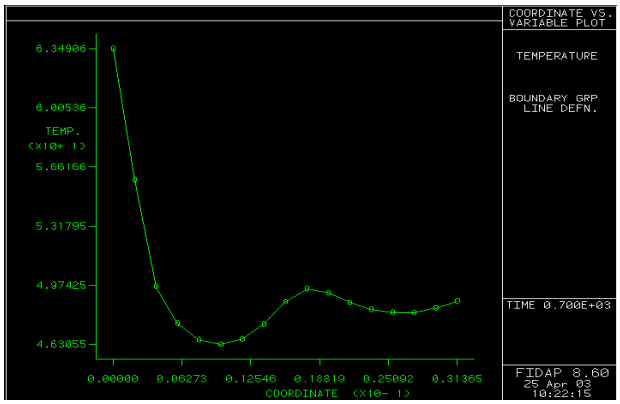


II. Temperature Profile along Tumor Edge for the three Meshes

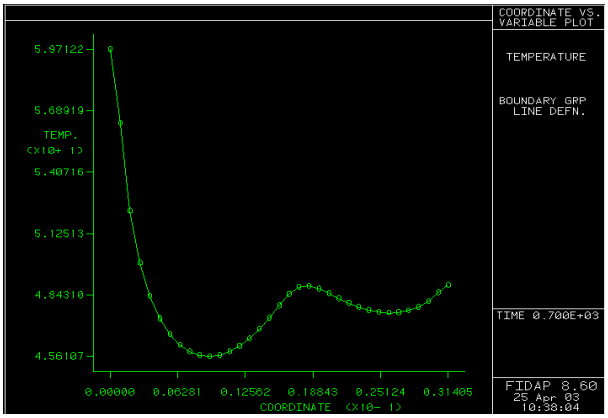
a) Voltage=0.27V at Time=700 seconds (freq9)



b) Voltage=0.27V at Time=700 seconds (freq10)



c) Voltage=0.27V at Time=700 seconds (freq11)

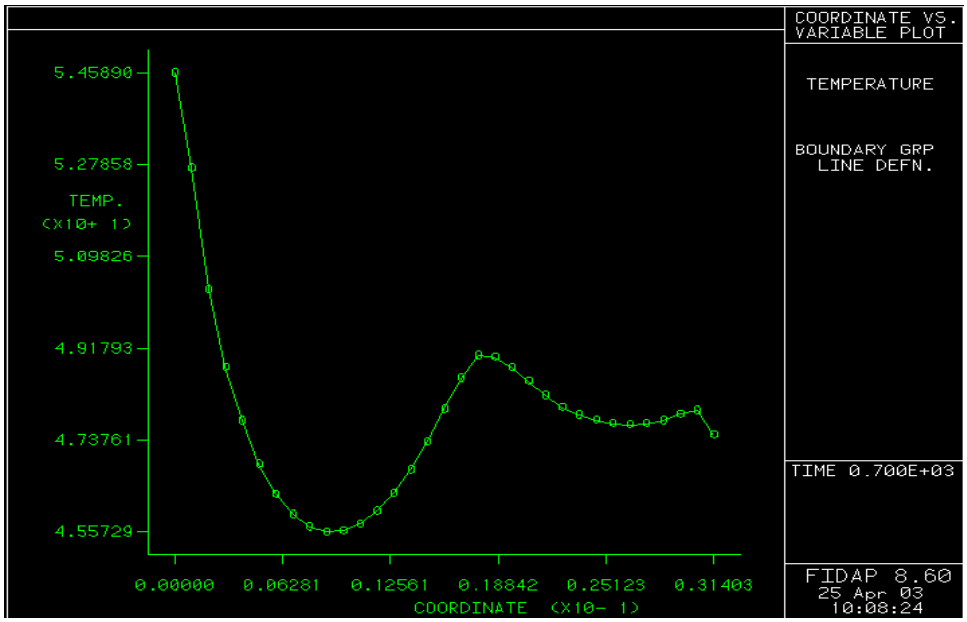


Discussion

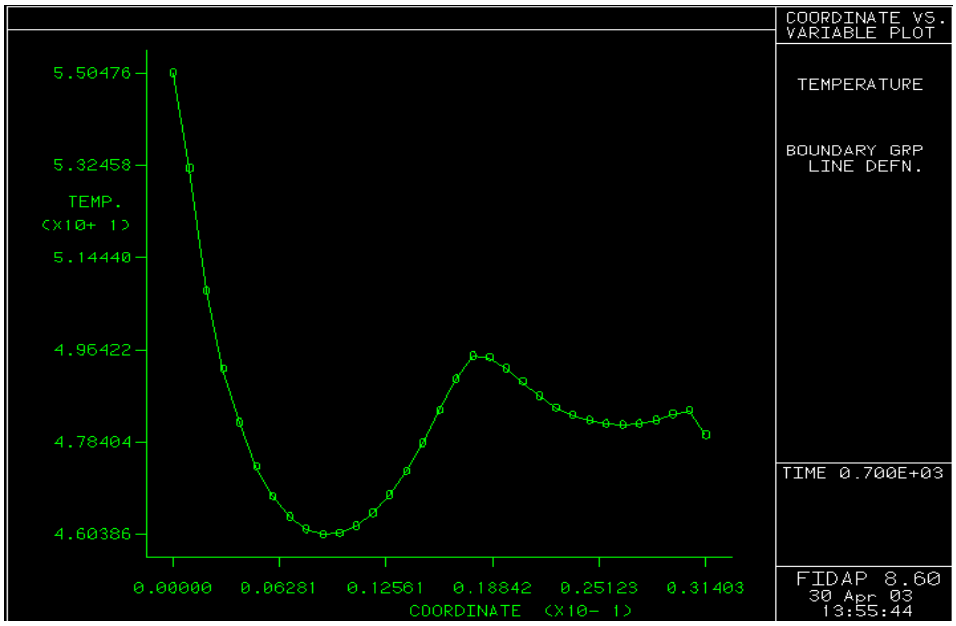
In the three cases shown on previous pages, we analyze the effect of the mesh size of T-shaped probe on temperature profile. So we start with mesh 1 (shown in the appendix) which is a rather coarse mesh. So to check if we need to reduce the size of the mesh further, we make the mesh finer. The resulting temperature profile clearly shows that by changing the mesh size, the temperature profile gets modified which should not happen in ideal case. So mesh 2 which is finer than mesh 1 should represent the results more accurately. However to be sure of the results we make the mesh finer in mesh 3. However there is not much change in the results which implies that mesh 2 is good enough to get accurate results without putting to much strain on computational time.

III. Variation with Thermal Conductivity

a) 0.27V for 700 seconds for conductivity of 0.54 W/mK



b) 0.27V for 700 seconds for conductivity of 0.60 W/mK (10% increase)



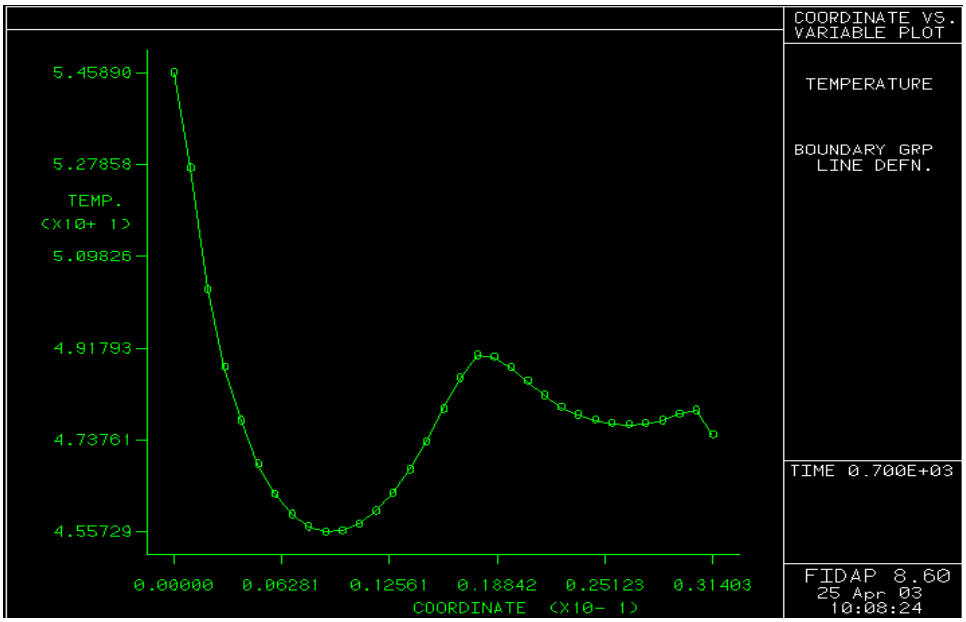
Discussion

On comparing the above two graphs, it can be seen that the when conductivity was increased to 0.6 W/mK (10% increase), temperature at the edge of the tumor varied slightly but remained above the critical temperature to destroy

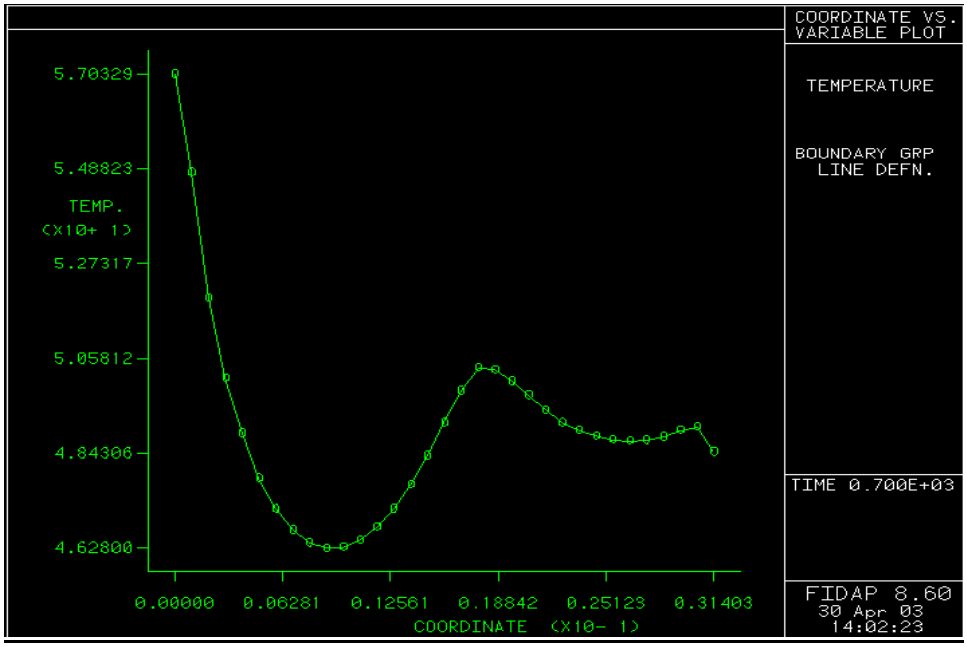
tissue cells in the tumor while protecting the kidney tissue. The maximum temperature at the edge increases from 54^0C to about 55^0C, but the increase in conductivity of 10% is not high enough to cause significant increase in the healthy tissue temperature. So again both the aims of destroying the cancerous tissue while maintaining the normal temperature of the healthy tissue are successfully achieved.

IV. Variation with Tissue Density

a) 0.27V for 700 seconds for tissue density of 1050 Kg/m^3



b) 0.27V for 700 seconds for tissue density of 1250 Kg/m^3



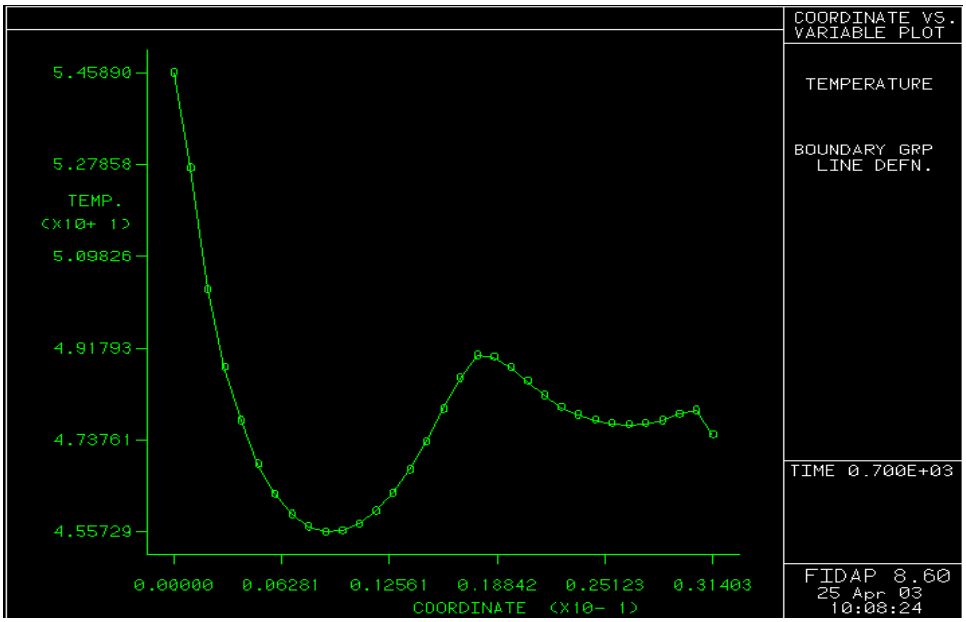
Discussion

When density was increased to 1250 Kg/m^3, temperature at edge of the tumor varied slightly but remained above the critical temperature to destroy tissue cells in the tumor while protecting the kidney tissue. The increase in the tissue density

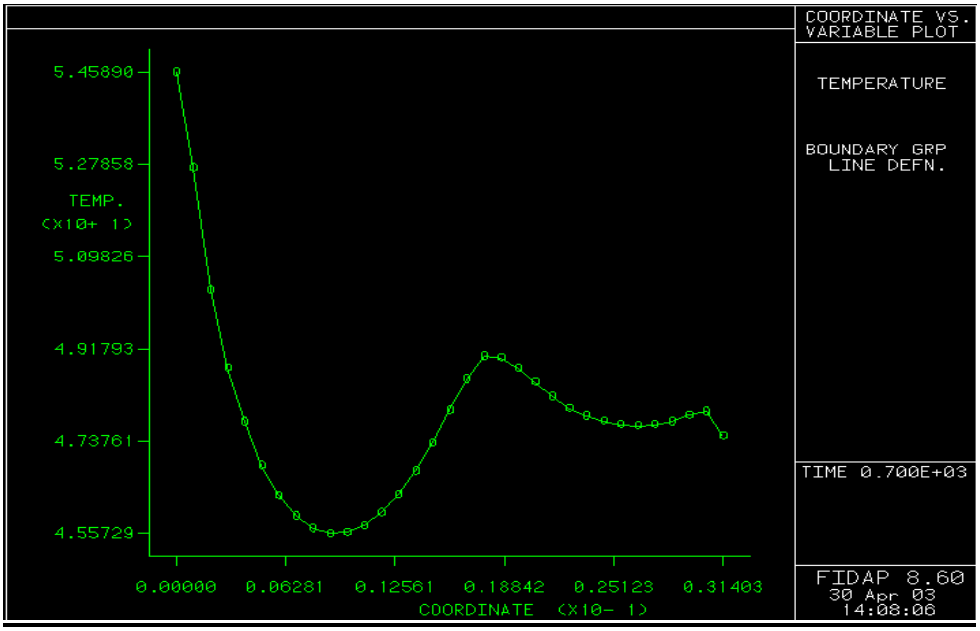
leads to an increase in the boundary edge temperature from about 54^0C to about 57^0C. Overall, variance of density was negligible in determining the final solution.

V. Variation with Number of Steps

a) 0.27V for 700 seconds for original number of iterations



b) 0.27V for 700 seconds for double the number of iterations



Discussion

Ideally speaking, the temperature profile for the tissue and the tumor should not change with the number of iterations. This is logical as the temperature

distribution is a physical result that should not depend upon the way used to obtain that result. So if the mesh and the time steps are small enough, the temperature profile should not depend upon them. So to check this we try to double the number of original iterations. As seen from the above two graphs, the results obtained are exactly the same irrespective of the number of iterations, which proves the validity of the rest of the results.

Appendix A

Boundary Conditions -

- Species flux=0 at the edges of the kidney
- Species concentration= 0.27V at the edge and end of the probe
- Species concentration=0 at the edges of the kidney

Initial Conditions -

- T=37^{o} C for the kidney and the tumor

Appendix B

Problem Command:

- Geometry Type: Axis-Symmetric
- Simulation Type: Transient
- Momentum Equation: No momentum
- Temperature Dependence: Energy and Species
- All other default variables were used

Because the probe is inserted into the center of the tumor and the tumor is assumed to be spherical we used axis-symmetric geometry.

Solution Command:

We used all of the default variables

Time Integration Command:

- NSTEPS:900
- TSTART: 0
- TEND:900
- DT:1

All other default variables were used

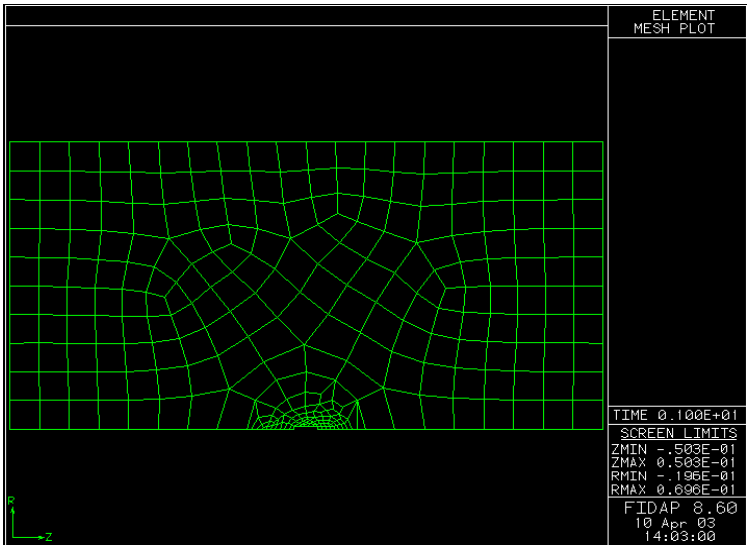
Entities:

The defined entities in this project were the kidney and the tumor. The probe was not defined as an entity because there was no temperature variation in it.

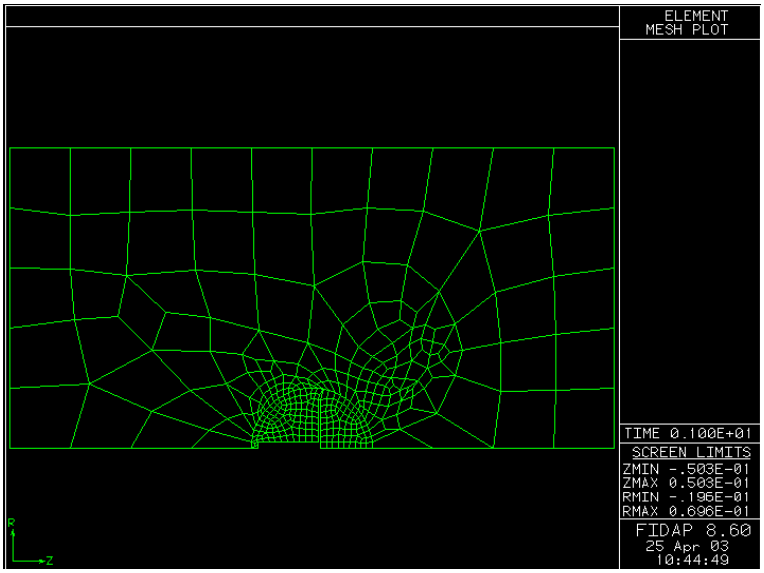
Appendix C

Meshes Used in the Analysis

- **Plot of the Original Mesh**



- **Plot of Mesh-2 (filename=freq 9)**

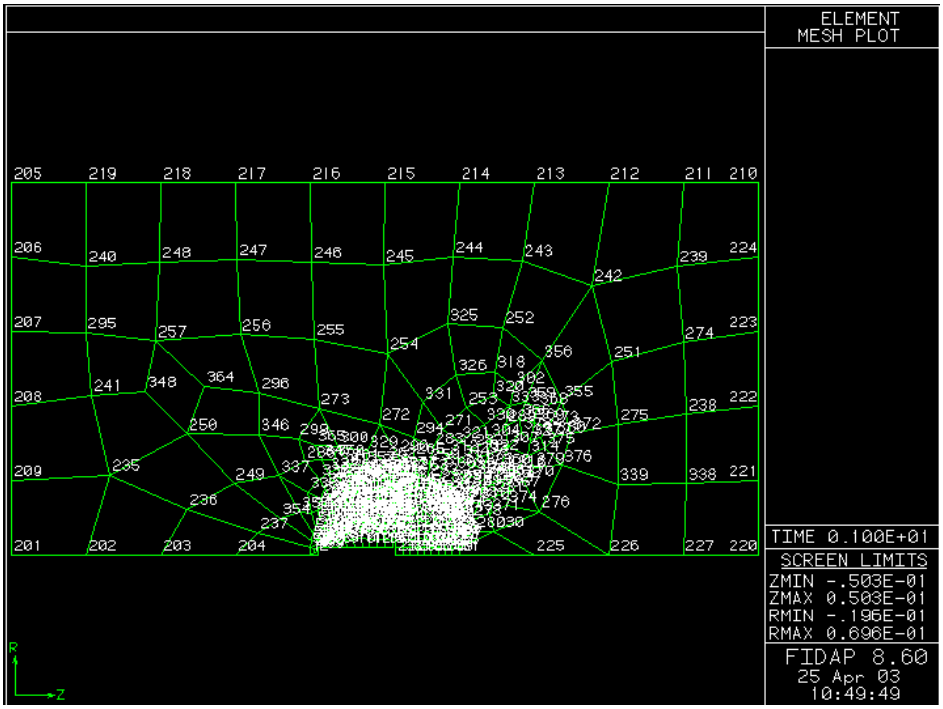


Mesh Details

Interval Size:

Region	Mesh1	Mesh 2	Mesh 3
Tumor	0.0099	0.005	0.002
Kidney	0.001	0.002	0.0009

Mesh with Node Numbers



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