Thermal Imaging and Analysis for Breast Tumor Detection

BEE 453: Computer-Aided Engineering:
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Executive Summary

Breast cancer is the most common cancer among women, except for non-melanoma skin cancers. Women in North America have the highest rate of breast cancer in the world and the chance of a woman developing this cancer is 13% (ACS). Resulting deaths have been decreasing mainly due to early detection and increased awareness. This study analyzes the use of a thermogram as a potential method for breast cancer detection. The breast is evaluated by an infrared camera and a temperature profile is produced. Proper study of the image can show if a tumor is present. A computer simulation of this procedure was used to model the temperature profile and its change as certain parameters vary. Results show that in the present of a tumor, there is a difference in surface temperature of the breast. Input values such as tumor size, tumor location, heat transfer coefficients, and perfusion rates were varied to determine the reliability of a positive result despite differences in each unique breast from woman to woman.

Introduction and Design Objectives

Background Information

Breast cancer is the second leading cause of cancer death in women. The chance that breast cancer will be responsible for a woman's death is about 1 in 33. According to the American Cancer Society, in 2007, about 40,460 women and 450 men will die from breast cancer in the United States. The key to effective treatment is early detection. Alternative methods for tumor recognition have been researched to couple with mammograms. When a mammogram was conducted alone, it produced a sensitivity of detection of 83 percent. When conducted with a thermogram, sensitivity increased to 93 percent, making it a worthwhile option to explore. This paper assesses the experimentation done by Ng and Sudharsan in 1999 titled "An improved three-dimensional direct numerical modeling and thermal analysis of a female breast with tumor."

Thermograms have been under investigation for a few decades, but are still being refined due to their high rate of false positives, although women with false positives have been found to be at a high risk of developing breast cancer. By imaging the breast and creating temperature profiles, variances in temperature on the surface of the skin can indicate the presence of a tumor.

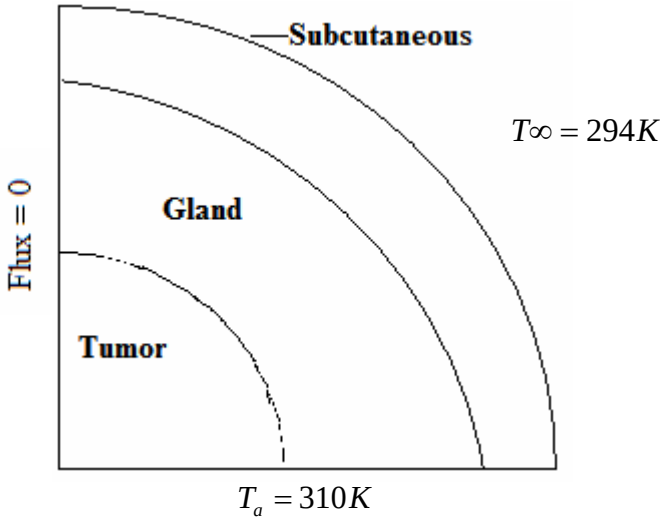
Design Objectives

The goal of this study is to evaluate the potential for a thermogram to be a viable method of breast cancer detection. By measuring the surface temperature under different conditions such as variations in tumor size, location, blood perfusion rate and heat transfer coefficient, we will be determining if the differences caused by these changes are significant enough to produce false positives, making the method ineffective, or if they are minimized to better predict the presence of a tumor. We examined the temperature difference between two points on the breast to determine if the area of the skin above the tumor was significantly higher than an area farther away from the tumor. COMSOL was used to calculate the desired results including the sensitivity analysis conducted to determine accuracy. We constructed a mesh for our geometry and included subcutaneous,

glandular and tumor areas to be modeled. Each area had its own properties that were considered in the equations. To simplify our model, we used a 2-D quarter circle for our geometry and assumed axis symmetry. After running the problem, variations were considered in the size, location, and certain properties of the tumor and its affect on the surface were compared and analyzed in graphs.

Problem Schematic

The breast was modeled as a 2-D axis symmetric with the tumor located along the y-axis for simplicity. Several tumor sizes were evaluated, as well as several locations for the tumors (Appendix C – Locations 1-5 for 30 mm tumor). The subcutaneous layer was 0.005m, the glandular layer varied from depending on the size of the tumor. See Appendix B for the mesh and mesh convergence.



The governing equation and boundary conditions are explained in Appendix A.

Results and Discussion

A sensitivity analysis was conducted to determine the effects that variations in tissue parameters had on the outcome of the thermographs. Examining for such differences allows checking the accuracy of the results. Our focus was the effects that the size of the tumor, the location, the blood perfusion rate of the tumor and the heat transfer coefficient have on the surface temperature of the breast.

Normal values used for analysis are shown in Table 1, and variations are discussed below.

Tissue Layer	$c_b w_b$ ($W/m^3 \cdot C$)	k ($W/m \cdot C$)	q_m (W/m^3)
Subcutaneous	800	0.21	400
Glandular	2400	0.48	700
Tumor (30 mm)	48000	0.48	5790

Table 1. Values used for blood perfusion, thermal conductivity, and metabolic heat production.

To determine whether certain parameters had any significant effects on the surface temperature measured, several sensitivity analyses were undertaken. The first figure shows the relationship between the tumor size and surface temperature at one fixed location that was chosen at which to perform an analysis. Only one location is shown here, but at different locations, the results had the same trend. At location one, which is near the surface and penetrates the subcutaneous region, as the size increases, so does the surface temperature. Within a reasonable range of tumor size, 10 – 30 mm, there is an increase of one degree Kelvin. Since the instrument that is used to measure the surface temperature is an infrared camera that has an accuracy rate of ±0.03˚C, it is likely that the slight increase in temperature is significant and can be correctly identified for tumor detection.

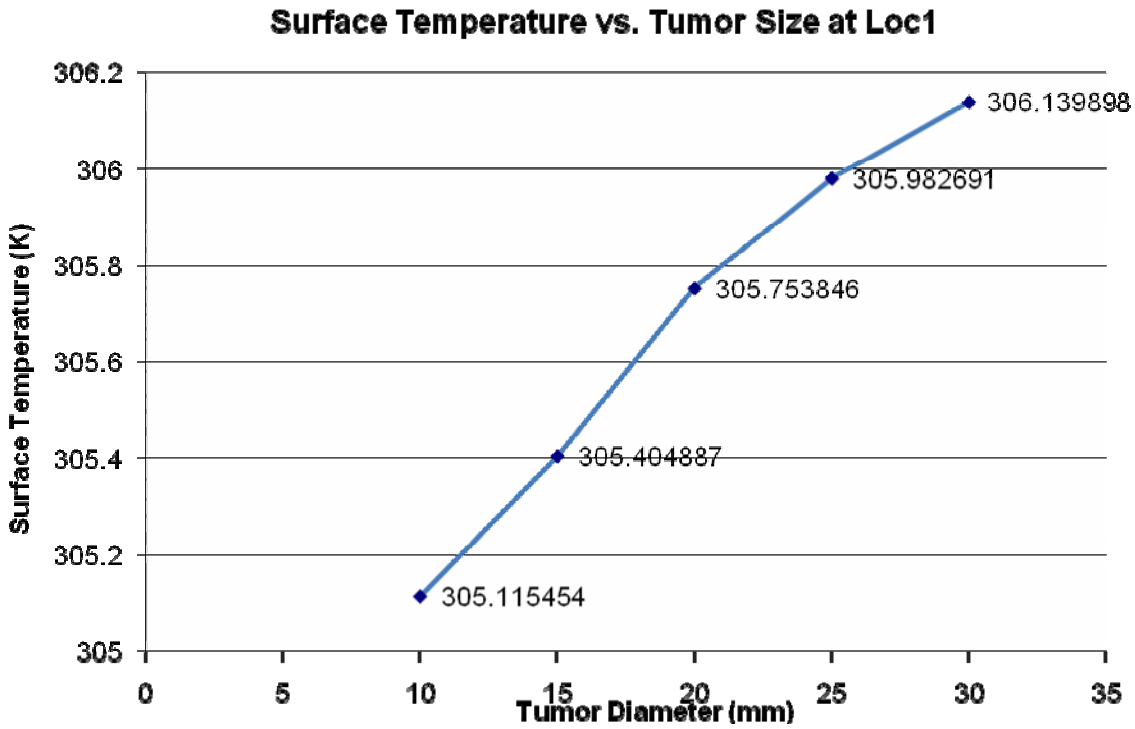


Figure 1. Surface temperature versus tumor size at location 1.

Figure 2 shows the relationship between the tumor location and the change in surface temperature that goes with each tumor location. Different locations (see Appendix C for details) change the surface temperature appreciably, from 306.14 K at location 1 to 302.71 K at location 5. Comparing Figure 2 to Figure 1, tumor location is a much more sensitive factor than tumor size. Our analysis will be based on the first two locations for optimum results.

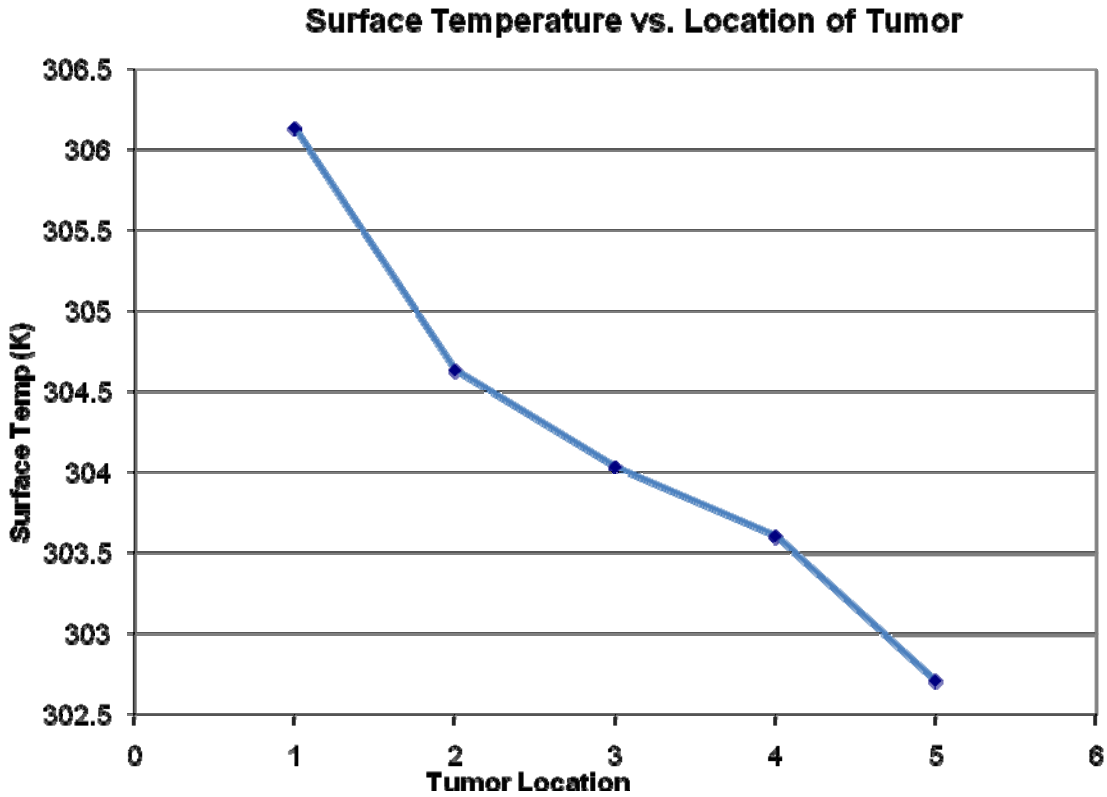


Figure 2. Surface temperature versus location of tumor as shown in appendix C.

For a relatively smaller size tumor, the blood perfusion rate has a more important impact on the surface temperature measurement than tumors of the larger sizes. However, thermograms are only an accessory to other detection methods, and most techniques today allow for detection of tumors that are larger in size. Thus, this project's purpose is to analyze whether or not smaller tumors can be discovered using thermal imaging coupled with other techniques. Table 2 shows the perfusion sets used.

Tissue Layer	$(c_b w_b)_1$ $(W/m^3{}^\circ C)$	$(c_b w_b)_2$ $(W/m^3{}^\circ C)$	$(c_b w_b)_3$ $(W/m^3{}^\circ C)$	$(c_b w_b)_4$ $(W/m^3{}^\circ C)$
Subcutaneous	800	1600	800	1600
Glandular	2400	2400	3600	3600
Tumor	48000	48000	48000	48000

Table 2. Sets of Perfusion values used for sensitivity analysis.

Perfusion set two varied the flow rate in the subcutaneous tissue layer, and this showed an increase in temperature that was expected (Figure 3). In addition, $(c_b w_b)_3$ also showed an increase in temperature from the normal set, but with a smaller amount. This proves that the perfusion rate of the subcutaneous region is the most important, which is the expected result.

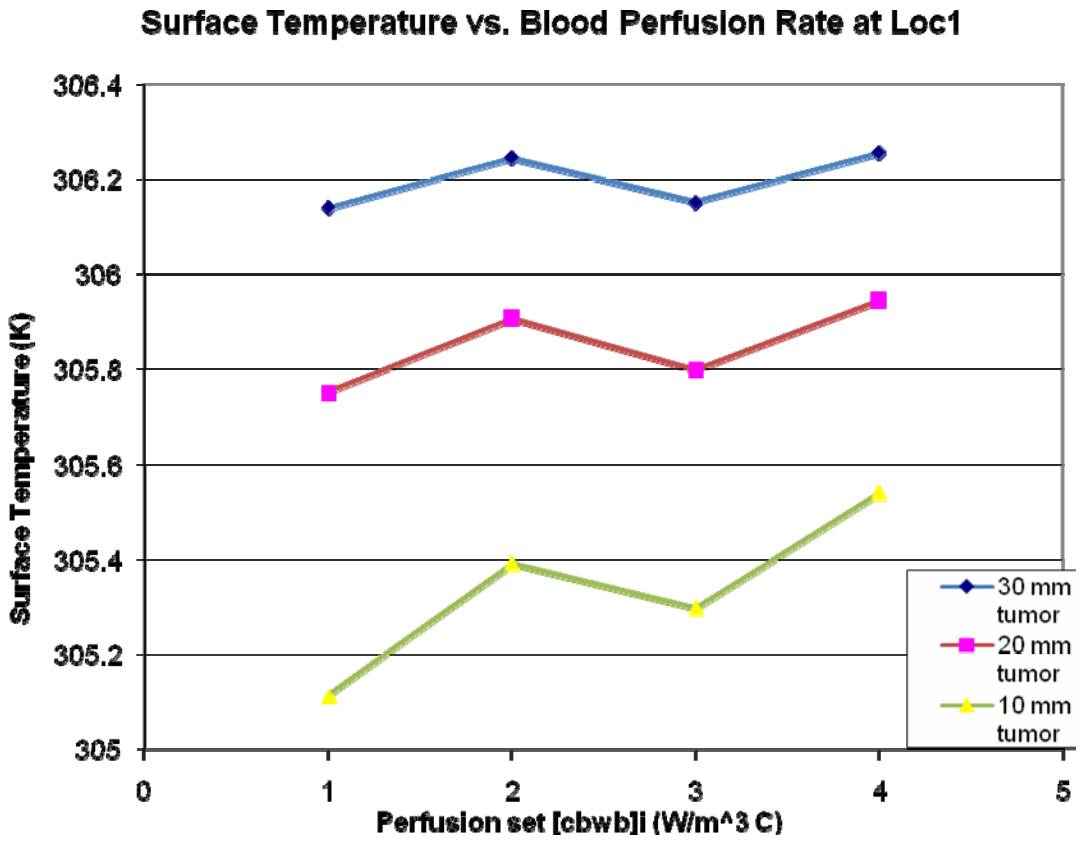


Figure 3. Surface temperature version blood perfusion rates at location 1 for the tumor.

Figure 4 shows the relationship between surface temperature and the value of the heat transfer coefficient. This was evaluated to determine how much the heat transfer coefficient affects surface temperature. As was anticipated, the higher the heat transfer coefficient the lower the surface temperature. The range of heat transfer coefficients was from 10.8 W/m^2°C to 16.2 W/m^2°C. A combined heat transfer coefficient at a value of 13.5 W/m^2°C was used to include the effects of convection, radiation, and evaporation.

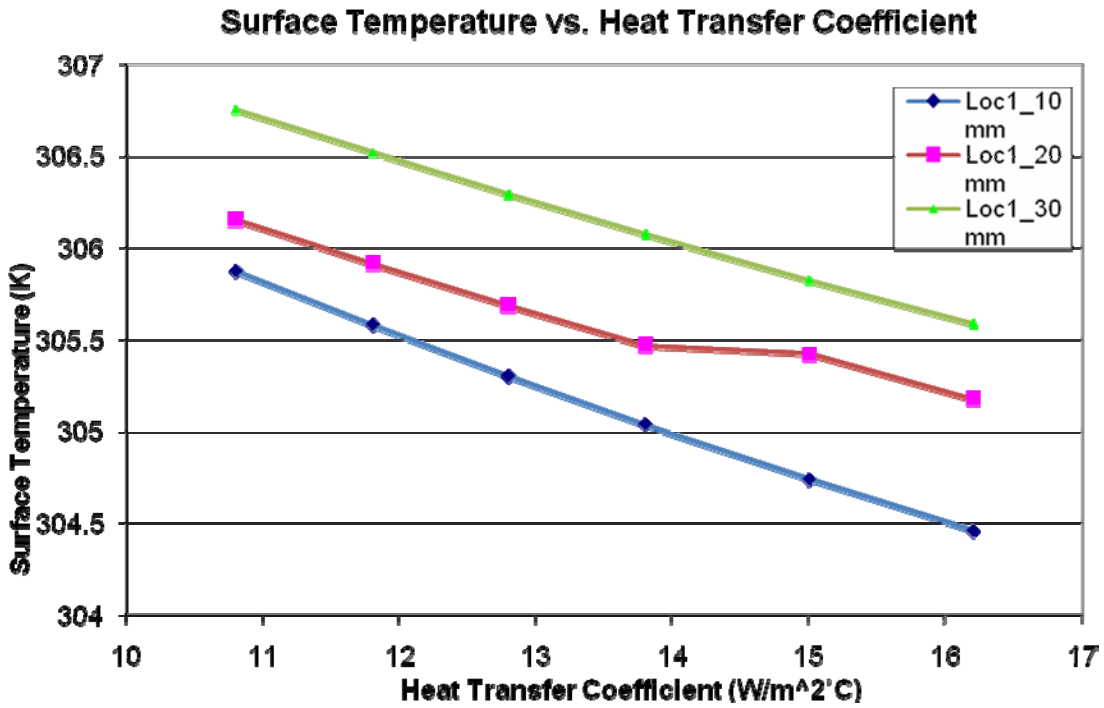


Figure 4. Surface temperature versus the heat transfer coefficient of the surface.

The values for the tumor doubling rate (t_d) were calculated using the following equation:

$$D = 0.01*\exp[0.002134(t_d-50)] \text{ [m]} \quad (2)$$

where D is the tumor diameter.

To calculate the metabolic rate (q_m), the following equation was used:

$$q_m*t_d = C \text{ [W day/m}^3\text{]} \quad (3)$$

where C is a constant equal to $3.27\text{x}10^6$ W day/m^3. Table 3 summarizes the values calculated using these equations for specific tumor diameters used.

Tumor Diameter (mm)	t_d (days)	q_m (W/m^3)
10	50	65400
15	240	13600
20	375	8720
25	479	6827
30	565	5790

Table 3. Values of the metabolic heat production terms calculated using equation 2 and 3.

Figure 5 shows the graph for the surface temperature versus tumor size using the values for the metabolic rate (q_m) that are shown in Table 3. This graph shows that the smaller the tumor, the more significant the perfusion rate would affect the surface temperature. Thus, for noteworthy results to detect smaller tumors, accurate perfusion rates are needed.

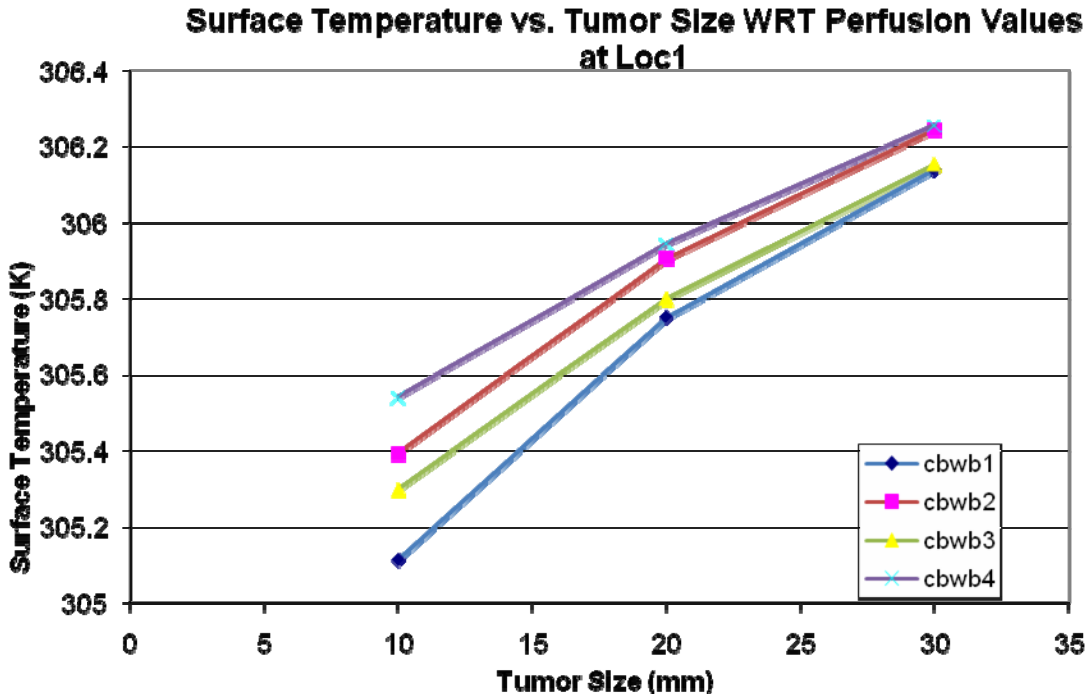


Figure 5. Surface temperature versus tumor size with respect to the perfusion values at location 1.

The study is based on the premise that there is a higher blood flow through the tumor than the rest of the breast. Its metabolic rate acts as a heat source. This causes the area to have a higher temperature as a result. The hypothesis is that the temperature will have an affect on the surface of the breast through heat conduction. Our aim is to model this heat transfer and compare the surface temperature of a breast with a tumor beneath it to the surface temperature on a normal area of the skin. Several factors can change the heat transfer profile on the surface of the breast. The blood perfusion rate of the subcutaneous tissue has the greatest influence, and the heat transfer coefficient is the next greatest contributor as seen in Figures 3, 4 and 5 above. Although the temperature discrepancy of only a few degrees may bee insignificant, it is important with respect to this study. A tumor of 10 mm at a location deeper within the breast caused only a 1.7 ˚C change in temperature on the surface. This is well within the range of the conducted

sensitivity analysis, indicating that a small tumor can be easily overlooked. Miscalculations or inadvertent fluctuations in this coefficient are what account for the 10% false positive/negative rates. Controlling these errors is difficult and is another drawback to this technique.

The results of this study show that in the presence of a tumor in the breast, there is a significant difference, 3 - 5 ˚C for a respective diameter range of 10 mm-30 mm, in the surface temperature of the breast above its location when compared to normal tissue. Analysis of thermographs can therefore be used to indicate the possible presence of a tumor within the breast, but it cannot be used as an accurate predictor because variations in the heat transfer coefficient, blood perfusion rate and tumor location that can be significant enough to throw off the temperature analysis. In actual practice, results may also not be so clear with variations in breast tissue like density and other normal inconsistencies, producing unexpected results.

Since a thermogram is not efficient enough by itself, a cold stress analysis was performed on the model that showed a 10 mm diameter tumor at location 1. For simplification, the external temperature was reduced to decrease the skin temperature, rather than cooling the skin by other means. The external temperature used was 265K and allowed to cool the skin for 30 minutes, with a time step of one second. Right after cooling, the skin was re-warmed by changing the external temperature back to 294 K, and run for another 30 minutes at a one second time step. Figure 6 shows a comparison of two points on the surface, the top curve closer to the tumor and the bottom curve of a point farther away from the tumor.

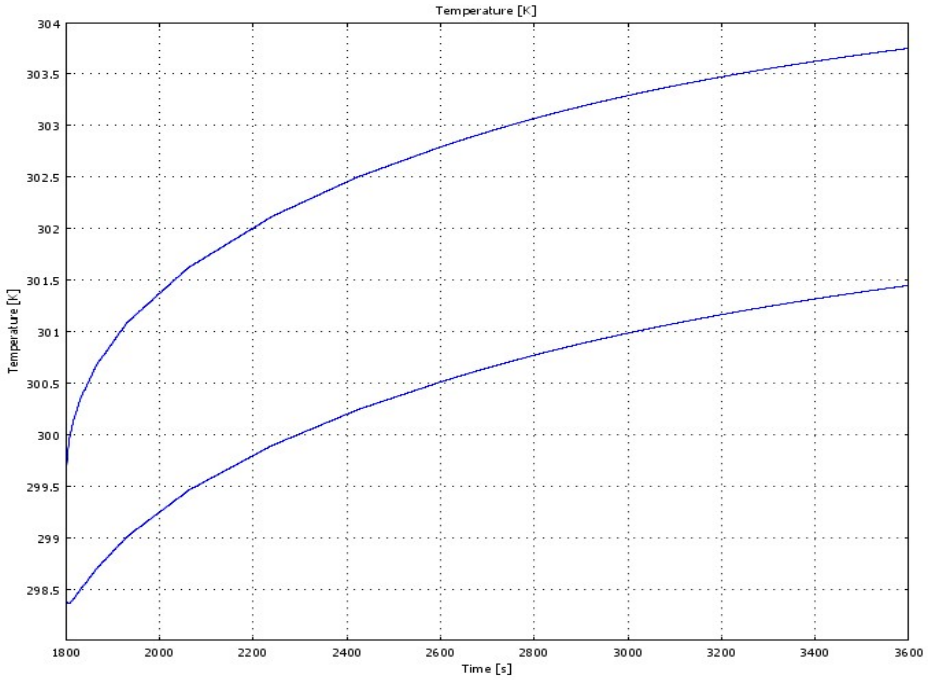


Figure 6. Re-warming of skin after cold stress for a surface point close to the tumor (top curve) and for a surface point far from the tumor (bottom curve) over 30 minutes.

As can be noted on the graph, there is an initial temperature difference of 1.3 degrees, but with a 2.3 degrees difference at 3600 seconds. For the steady state solution that was shown earlier (Figure 1), the temperature for the point closer to the tumor was 305.11 K. The temperature for the point farther away from the tumor was 303.40 K. The temperature difference is thus only 1.71 degrees, and is about 0.6 degrees less of a difference from the transient solution with cold stress applied. With instruments that can detect a disparity of this size (±0.03˚C), cold stress analysis may be a relatively good method to couple with thermograms to enhance tumor detection.

Conclusion and Design Recommendations

Breast cancer is a disease that needs to be caught early, but many women may deter from being examined due to economic factors, lack of convenience and discomfort with traditional exams such a mammograms. Thermography is an affordable option that is easy to run and causes minimal distress to the patient. Mammograms are known to cause pain and while they are and effective means of detection, their use can be minimized by thermograms. If thermography can get to a point where it is reliable enough to indicate the lack of a tumor confidently, then the need for a mammogram would be eliminated. If the thermogram indicated a possible tumor, then a mammogram could be conducted as the next step to either confirm or reject the claim. Such an option may make women more inclined to be examined for cancer if the hassle and discomfort were eliminated from the procedure.

According to our results, thermograms are better off as a supplement to other forms of detection because of the variability in certain parameters. The blood perfusion rate in the subcutaneous tissue can vary as much as one degree depending on the size and location of the tumor. This difference is enough to create a false positive upon analysis or miss a tumor all together—an obvious problem in the procedure.

Future studies can be performed to further determine if thermograms provide accurate enough results, and if so, what kind of error they produce. Different factors such as variations in ambient air temperature, air flow around the breast, whether the patient is sitting up or lying down, density of the breast and cysts can all be considered in their effects on surface temperature.

Appendix A – Mathematical Statement of the Problem

Geometry and schematic:

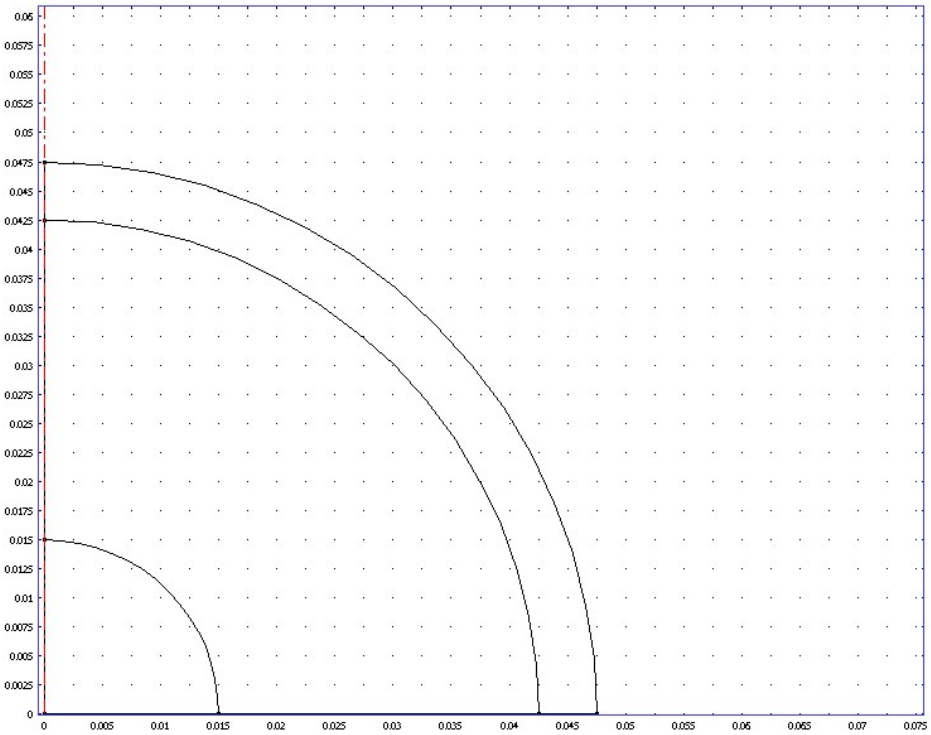


Figure 7. Schematic of breast with tumor.

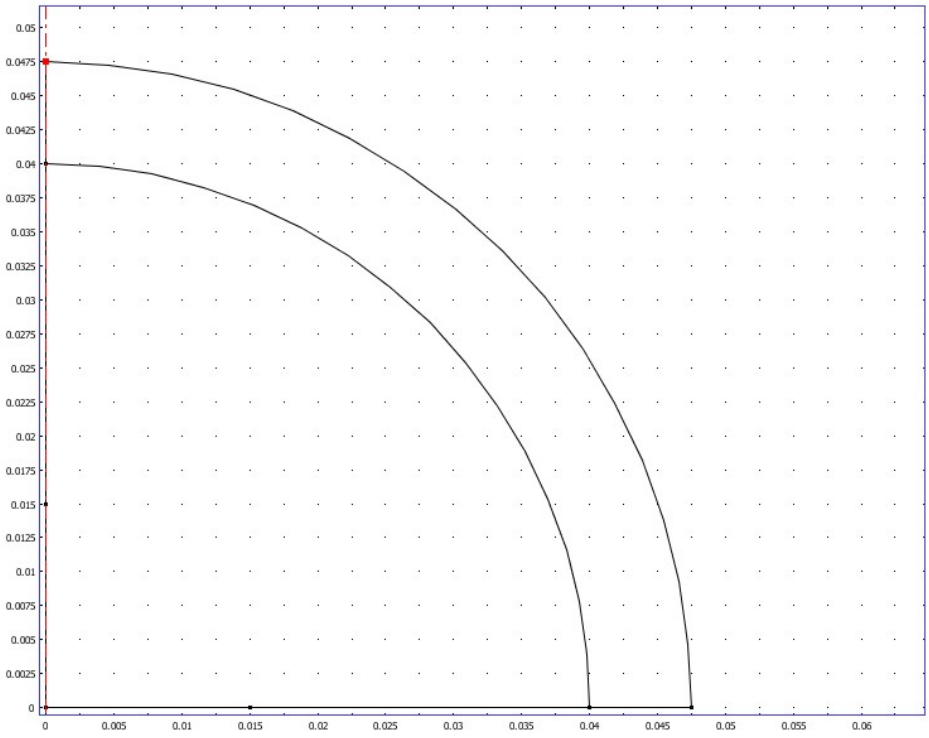


Figure 8. Schematic of a breast without the tumor.

Governing Equation:

$$k\nabla^2 T - c_b w_b (T - T_a) + q_m = 0 \quad (1)$$

The bio-heat equation presented above includes the heat transfer by conduction through the tissue, the volumetric metabolic heat generation of the tissue and the volumetric blood perfusion rate. The temperature of the artery is approximated as the core temperature of the body and the venous temperature is approximated as the local tissue temperature.

The boundary conditions are $T=T_a$ on the thoracic wall and $-k\nabla T = h(T - T_e)$ on the surface.

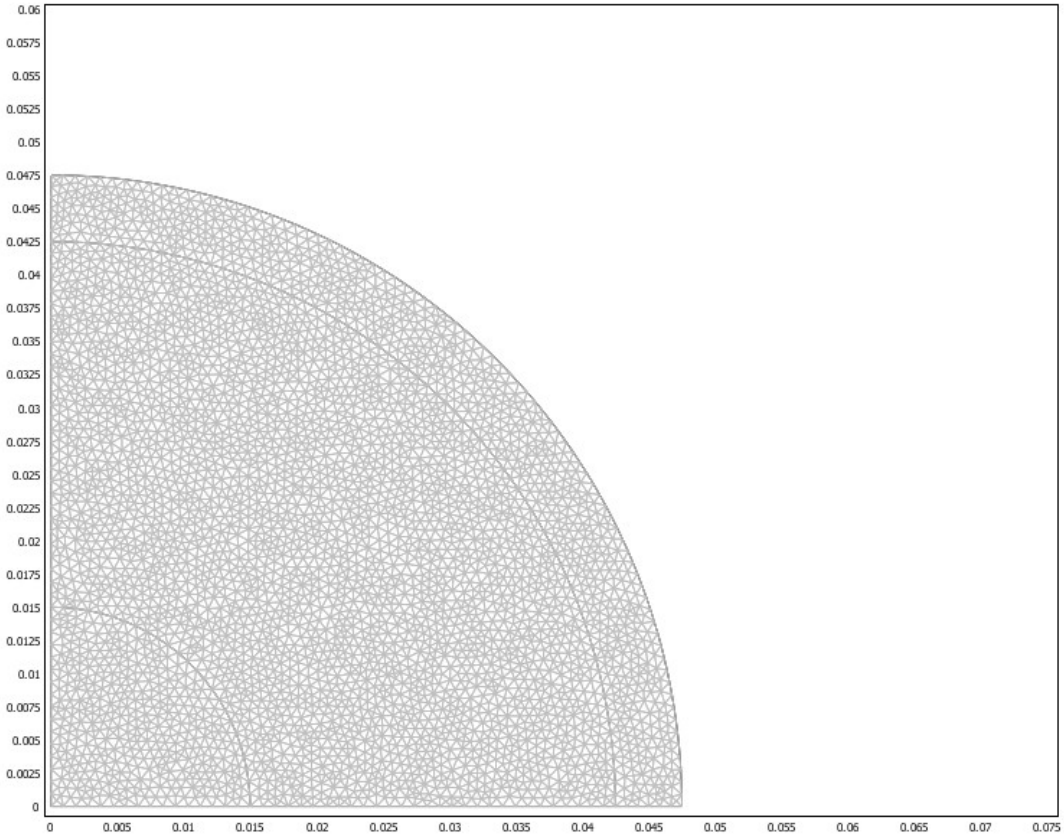
Table of Input Parameters:

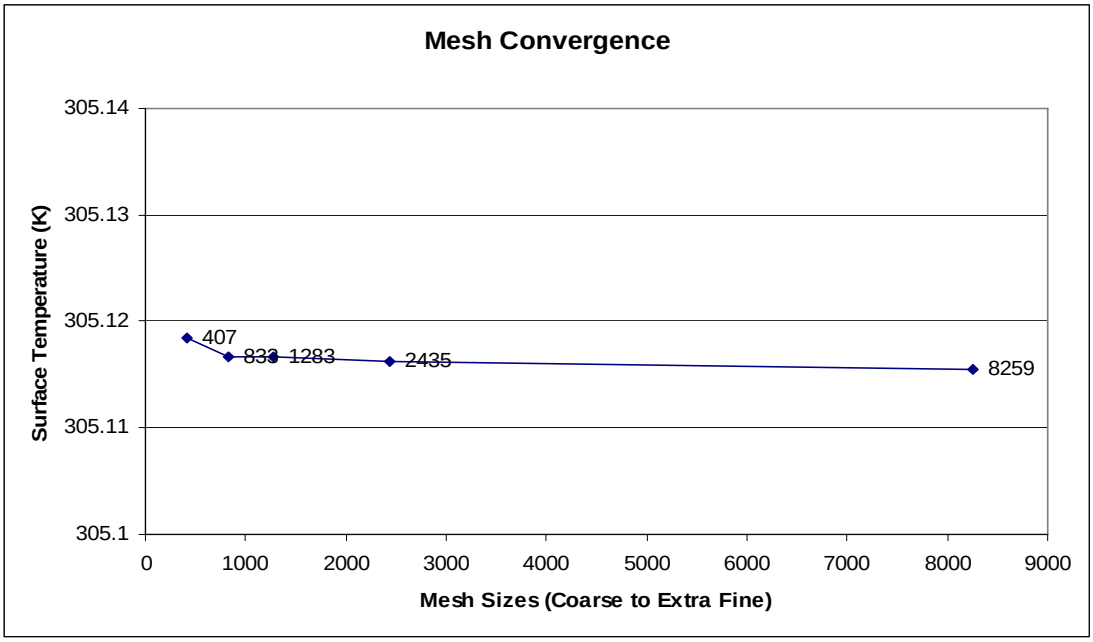
Variable	Value	Significance	Source
D	30 mm	tumor diameter	Ng, Sudharsan 1999
k_{sub}	0.21 W/m˚C	subcutaneous thermal conductivity	Ng, Sudharsan 1999
k_{gland}	0.48 W/m˚C	glandular thermal conductivity	Ng, Sudharsan 1999
k_{tumor}	0.48 W/m˚C	tumor thermal conductivity	Ng, Sudharsan 1999
q_m	5500 W/m^3	metabolic heat production	Ng, Sudharsan 1999
h	13.5 W/m^2˚C	heat transfer coefficient	Ng, Sudharsan 1999
$(c_b w_b)_{sub}$	800 W/m^3˚C	blood perfusion in the subcutaneous region	Ng, Sudharsan 1999
$(c_b w_b)_{gland}$	2400 W/m^3˚C	blood perfusion in the glandular region	Ng, Sudharsan 1999
$(c_b w_b)_{tumor}$	48000 W/m^3˚C	blood perfusion in the tumor	Ng, Sudharsan 1999
T_e	294 K	environmental temperature	Ng, Sudharsan 1999
T_a	310 K	arterial temperature	Ng, Sudharsan 1999
C	3.27x10^6 W day/m^3	constant	Ng, Sudharsan 1999
t_d	565 days	tumor doubling rate	Ng, Sudharsan 1999

Appendix B

COMSOL was used to solve the two dimensional axisymmetric problem.

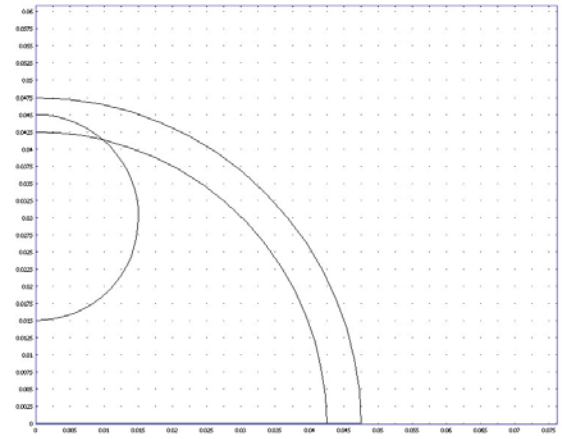
A triangular mesh element was used and a sample of the mesh plot is shown below:



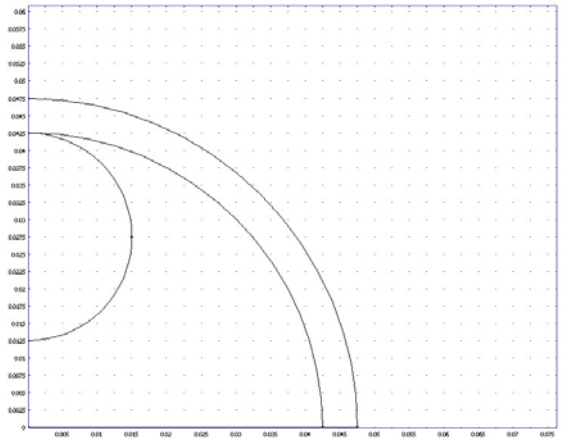


Appendix C

Tumor locations:



LOCATION 1



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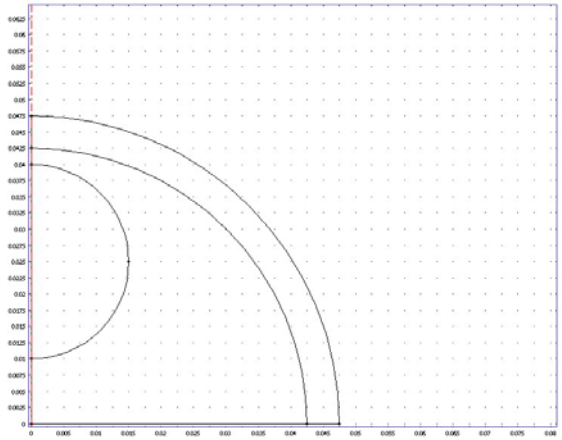
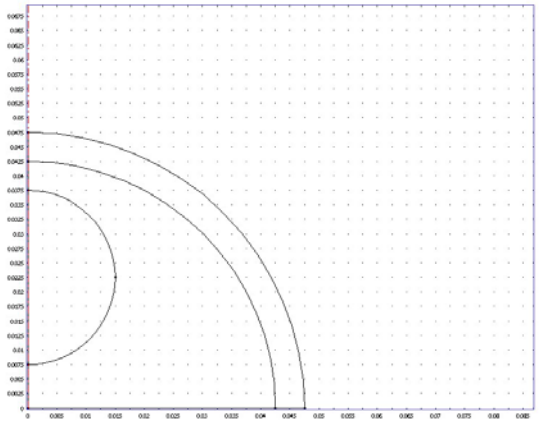


LOCATION 3



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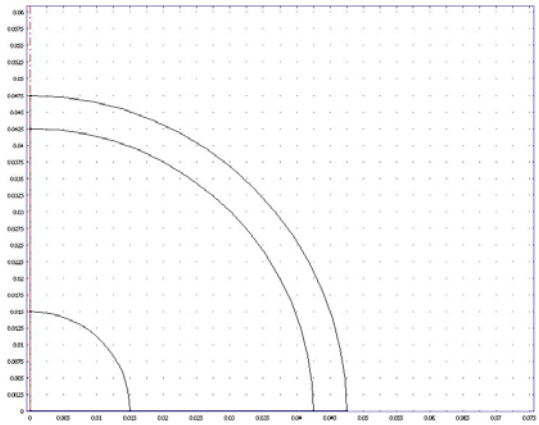

LOCATION 5

Appendix D – References

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