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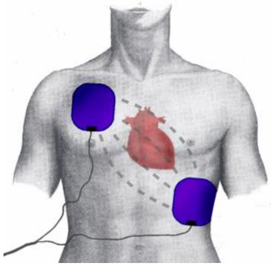

# Thermodynamic Effect on Dermal Layers Following Defibrillation of Heart

Computer Aided Engineering: Applications to Biomedical Processes

BEE 4530

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## Executive Summary

Much research and experimentation has made ventricular defibrillation a very well-studied process in terms of quantifying its effects on the heart. Yet, few researchers have looked into the potentially severe burning on the skin that can result from defibrillation. Because many have overlooked this problem, we chose to model the effects of defibrillation on the skin. The elimination of this painful side effect is an opportunity for design optimization. The following report illustrates our two goals: the development of a method to quantify the dermal burning associated with defibrillation, and the development of a better design for modern defibrillators to reduce dermal burning.

We accomplished our first design objective by measuring the variation of three quantities over time in our model: the applied voltage, the heat conduction through the skin due to resistive heating, and the amount of thermal injury in the skin as a result of this heat conduction. This required us to couple three physics in COMSOL: conductive media physics to incorporate the voltage equation, heat conduction physics, and the diffusion equation (to quantify the burn by treating thermal injury as a zeroth-order diffusion problem). In order to accomplish our second design objective, we used our model to vary the thickness of the gel applied on the skin prior to defibrillator to determine if a higher gel thickness would result in less thermal injury in the skin layers.

Through this process, our first design objective was satisfied by considering burning to occur in regions where the thermal injury concentration was greater than 0.53. In imposing this threshold, we found that first degree burns do occur on the skin, on areas of the epidermis right beneath where the defibrillator paddles are placed. We also used temperature to quantify the burn, finding that the skin temperature in the burning regions initially increased with time due to the conduction of heat from the epidermis, and then decreased with time due to the conduction of heat to other areas of the skin. For our second design objective, we found that the gel layer thickness reduced the maximum temperature from 328K at a 0.5mm gel thickness, to 316K at a 1.5mm gel thickness. As the thickness of the gel layer was increased, the patient's burns became significantly less severe, with a maximum concentration of 1e5 with a 0.5mm gel thickness, and a minimum concentration of close to 0 with a 1.5mm gel thickness.

Therefore, we found that the gel applied prior to defibrillation is pivotal in preventing cutaneous burns. Future work then includes customized settings for the age of the patient, skin type of the patient, and type of gel applied, all of which are parameters that can be easily adjusted in our model.

## Introduction

Defibrillators send an electrical pulse through the body to resuscitate the heart during life-threatening cardiac conditions, such as arrhythmias (irregular heartbeats), ventricular fibrillation (irregular muscle contraction in the ventricles), and pulse-less ventricular tachycardia (cardiac arrest). The voltage difference between the defibrillator and the heart causes the heart's muscle fibers to start contracting simultaneously, reviving the organ. Heat is conducted through each layer of the skin via resistive heating whereby each layer of skin and the applied gel act as resistive elements against the flow of energy. As a result of the temperature gradients created, additional heat conduction ensues.[1] Since most published papers with respect to defibrillators concentrate solely on the effect on the heart itself, it is often surprising that the effect on the skin has not been further explored. We became interested in this problem further after learning of a case in which third degree burns were found on a 62 year-old patient because amateur personnel hastily placed defibrillator paddles on her chest without applying the cream-like gel first. The burns formed on the patient after the shock from which, thankfully, she was able to recover. We decided that the issue of post-defibrillation cutaneous burning was too widespread to simply ignore, and began work on modeling this potentially harmful side effect. Even though there are few published articles that present data that study this process, and none that develop computational models, our group saw this as a challenge we were willing to take on.

We were able to find some experimental data, performed by Ambler et al, whose group has published numerous papers on studies that better quantify this problem. In one of their earlier studies, 83 patients experiencing atrial fibrillation were given multiple shocks ranging from 50 to 360 J. In order to quantify the burn, they recorded three quantities post-defibrillation: skin temperature recordings, the measurement of a pain detection threshold, and a visual analog scale (VAS) given as a questionnaire to the patient. Eighty-four percent of patients had some degree of pain after the procedure, with 23% experiencing moderate to severe pain, confirming the conclusions of their previous studies that cited pain as a significant problem. .[2] Ambler et al. then performed a double-blind, controlled study to investigate how effective two different types of cream were at preventing the burns associated with defibrillation. The two creams used in the experiment were a steroid cream betamethasone 0.1% and an aqueous (water-based) cream. The results from this study helped us validate some assumptions in our model.

Thus, we wanted to fully understand the effect that defibrillation has on the patient's skin and then use this knowledge in order to optimize gel thickness to reduce cutaneous burns. COMSOL was used to simulate the effect that the applied voltage has on the skin and allowed modifications in the gel thickness to understand its consequence. The model also accommodates a wide range of applied voltages from the defibrillator, since operators have different settings to select depending on the type of cardiac arrest and the condition of the patient.[3] This model not only helps to gain knowledge of the problem of burning following defibrillation, but aided us in our eventual goal to create a model that allows defibrillator manufacturers to improve the design of paddles based on the results of the model.

## Design Objectives

There were two main goals we wanted to accomplish through this project. The first goal was to model the defibrillation process as accurately and effectively as possible to clearly understand the temperature variation and quantify the burn in the skin layers. Through our COMSOL simulations, we were able to qualitatively understand where thermal necrosis occurred in the skin. We did this by first solving the heat transfer governing equation for temperature gradients following defibrillation, and then coupling those temperature gradients with the diffusion physics in order to quantify the burn as zeroth-order reaction. The second goal was to either reduce or (if possible) completely eliminate burning following defibrillation, by optimizing the design of defibrillators on the market today. We hypothesized that increasing the thickness of the gel would significantly reduce the burning following defibrillation. Although the gel is typically applied strictly to enhance the conductivity of the skin and make the defibrillation process more efficient, we hoped to prove that the gel can also be used as a region of heat dissipation, reducing the amount of heat that enters the skin layers. This way, the gel would prevent unnecessary burning.

### *Schematic*

In order to create a model that would most effectively accomplish our goals, we chose to model a cylindrical section of skin, since we are focusing specifically on the three layers of skin and not the heart. We modeled the dermal (middle) and subcutaneous fat (inner) layers, in order to maintain as much accuracy in our model as possible. We chose to remove the epidermal layer from the model because the region was so small there was no significant temperature, voltage, or burn variation within it. Orders of magnitude smaller than the rest of our dimensions, the epidermis was negatively affecting the smoothness of the mesh, and thus, the accuracy of the solution. Instead, in our analysis, we chose to consider the topmost layer of the dermal layer as the epidermis, so even though our schematic doesn't have a physical layer for the epidermis, we are considering its existence to be implicit in the model. The layer of gel sits above the dermal layer, acting as a primary the focus in our model's design. We assumed the model was axisymmetric and two-dimensional, with metabolic heat generation considered negligible.

Resistive heating defines the defibrillation process. We had to take into account the resistivities of each layer of the skin that the voltage passes through. We modeled this by coupling heat conduction and the voltage equation in COMSOL, and considered the entire process to be transient. We later added in the diffusion equation to model the burn injury. Since we had three processes coupled, we needed temperature, voltage, and concentration boundary conditions for our model. In terms of temperature and heat conduction boundary conditions, we set the top of the model (that was exposed to the atmosphere) as an ambient heat flux condition using the heat transfer coefficient specified on the schematic. We then set the bottom edge of the model (the bottom portion of the subcutaneous fat layer) and the right edge on the schematic to be at body temperature, since both of those regions are indeed inside the body. For the voltage boundary conditions, we considered the top edge of the gel layer to be the voltage applied by the defibrillator paddles. We set the bottom edge of the model to be the voltage at the heart, making the simplification that we could neglect the resistances of any internal tissues or organs between the heart and the bottommost skin layer. All other edges were considered to be electrically insulated. Finally, for the diffusion equation, we set all the edges to have the "Insulation/Symmetry" boundary condition, and set all initial concentration values to zero (because there is no thermal injury initially).

The schematic and all boundary conditions are shown below (and the governing equations are discussed in detail in the Appendix).

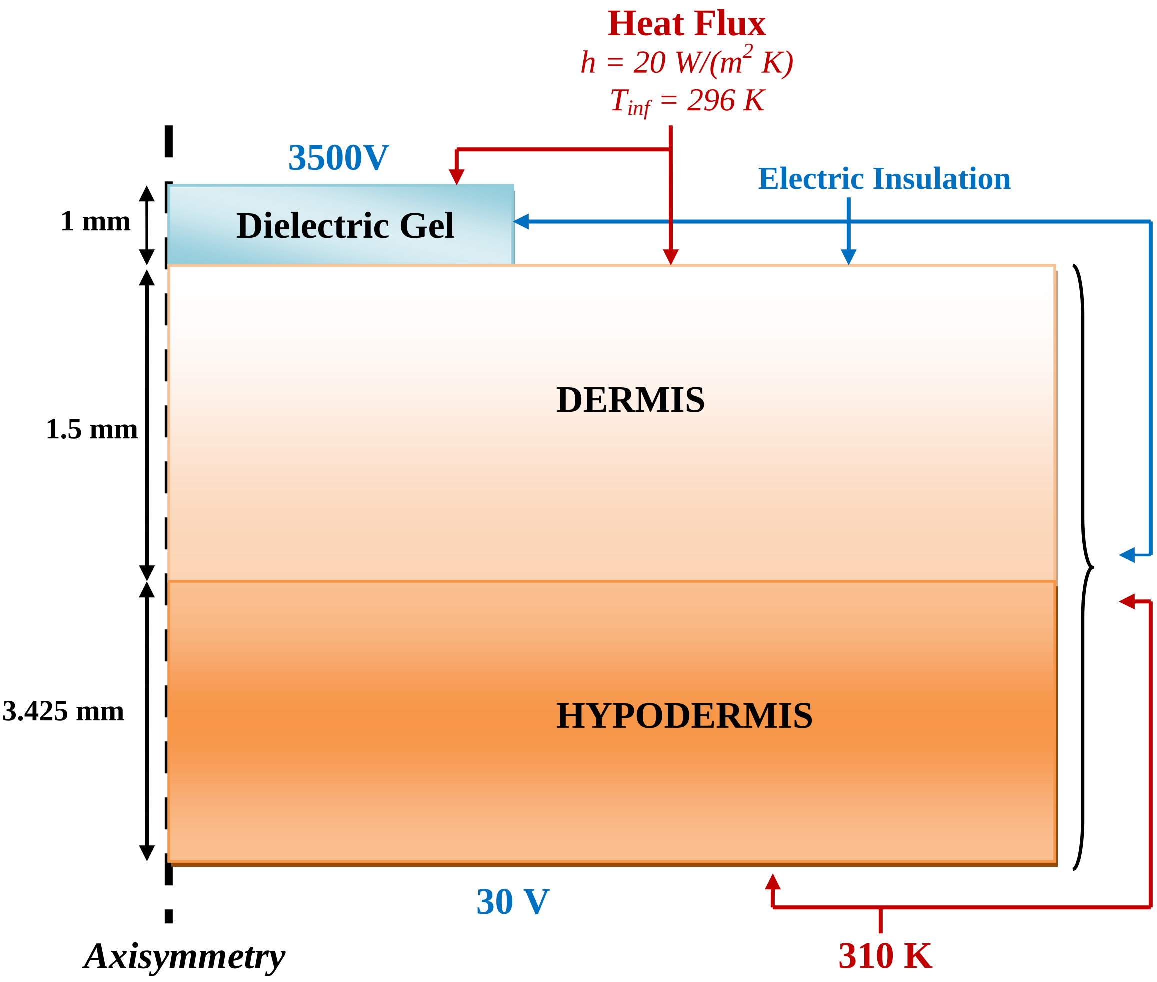

**Figure 1:** Schematic of model, showing all boundary conditions

## Results and Discussion

### *Design Objective #1: Quantification of Burn*

Since we are implementing three physics within COMSOL, heat conduction, mass transfer (burn injury calculation), and conductive media (voltage application), we generated three types of plots: temperature, voltage, and thermal injury plots. The temperature plots allow us to accurately quantify where the highest heat occurs due to the resistive heating and subsequent conduction. The voltage plots are used mainly to verify the boundary conditions as shown on the schematic. And finally, the thermal injury plots are used as visualizations for the exact locations of burning.

Temperature Reaches Highest Values at Dermis Layer

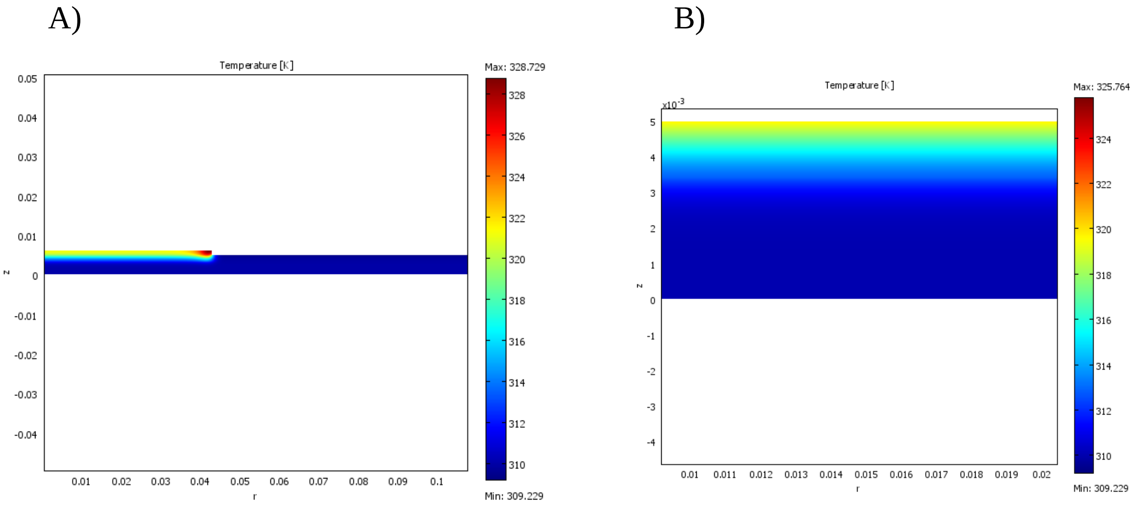

**Figure 2:** The above temperature profiles were obtained for a shock of 40ms, running the solution for 6s, with a defibrillation of 3500V. (B) is a magnification of the region of most change in (A).

The temperature profiles are transient between the top layer (the gel) and the bottom layer (hypodermis). The temperature in the model reaches a maximum value of 322K after 6 seconds. The sharp corner between the edge of the gel and the dermis creates a region of computational error due to the nature of the sharp edge. The results in this region, and the results that are direct effects of the numerical error within this region, are ignored for the purposes of our report. Ignoring the aforementioned computational errors, the heat conduction has a normal profile through the skin. This is the first result that verifies that there is heat flux from the paddle to the skin, producing burn at the epidermis. The shock generates heat, but the temperature profile remains normal in layers below the dermis, demonstrating that the temperature gradients do not spread much during this process. We also found that the gel layer contains the highest temperatures in the model. Since we were unable to attain the actual material properties of the gel, and because we found a Material Safety Data Sheet (MSDS) indicating that it is primarily composed of water, we modeled the gel as water, for all properties except for that of electrical conductivity. We also found information from the American Heart Association that instructed defibrillator operators to use a piece of gauze soaked in 0.9% saline if the gel was not available to them[8]. With that information, we chose the electrical conductivity to be that of 0.9% saline. Since 0.9% saline is 99.1% water, our assumption of modeling the other gel properties with those of water again seems reasonable. Further discussion of this choice is detailed in the accuracy check section towards the end of this paper.

Although most of the heating is in the gel region only, Figure 2.B plots just the dermal layers without the gel, which makes it clear that the maximum temperature in the skin reaches 322K. This temperature indicates first-degree burning, and is also consistent with Ambler's experimental findings that the burns are produced due to the defibrillator application.

The heat generation term in the energy conservation equation is a function of voltage, Therefore, we plotted the voltage gradients to see the effect of temperature as well as to ensure our model was properly implementing the given boundary conditions shown on the schematic.

Voltage Contours Verify Boundary Conditions

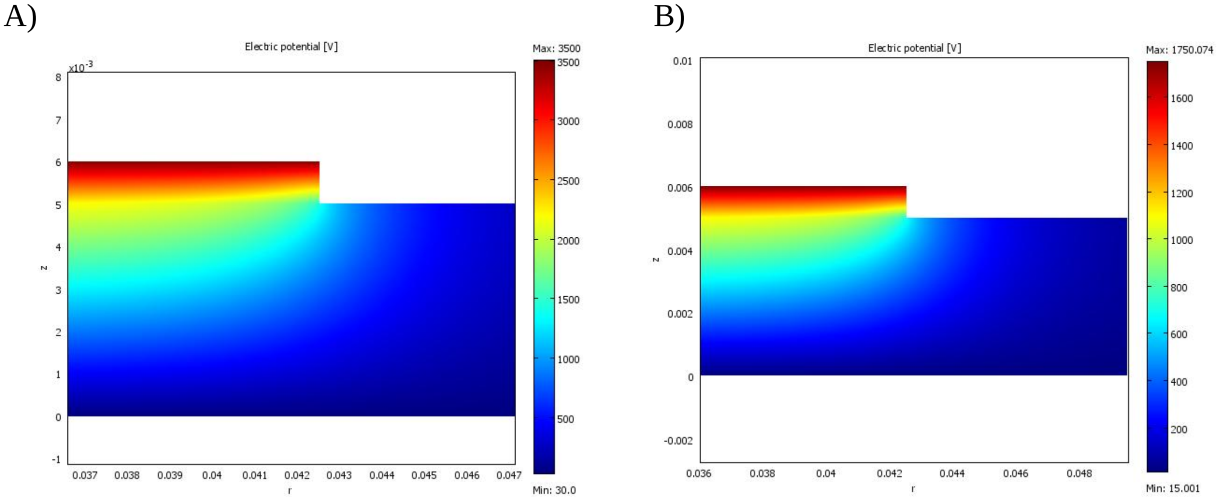

**Figure 4:** The above voltage profiles show the voltage variation in the skin. (A) shows the voltage variation as soon as the defibrillation of 3500V was applied. (B) shows the voltage variation 50 ms after the shock, as the voltage gradually starts to decrease down to 0 V.

Figure 4.A shows the voltage immediately after the shock is applied by the defibrillator. The voltage varies from 3500V (the amount of shock) down to 30V (the voltage at the heart), which logically makes sense. Figure 4.B shows the voltage profile 50ms after the shock. As expected, the voltage gradually decreases (and eventually hits 0 across the model about 20ms later). These plots show that our model is indeed modeling the voltage application of defibrillation correctly, and that our results are consistent with the boundary conditions.

Thermal Necrosis due to the defibrillator

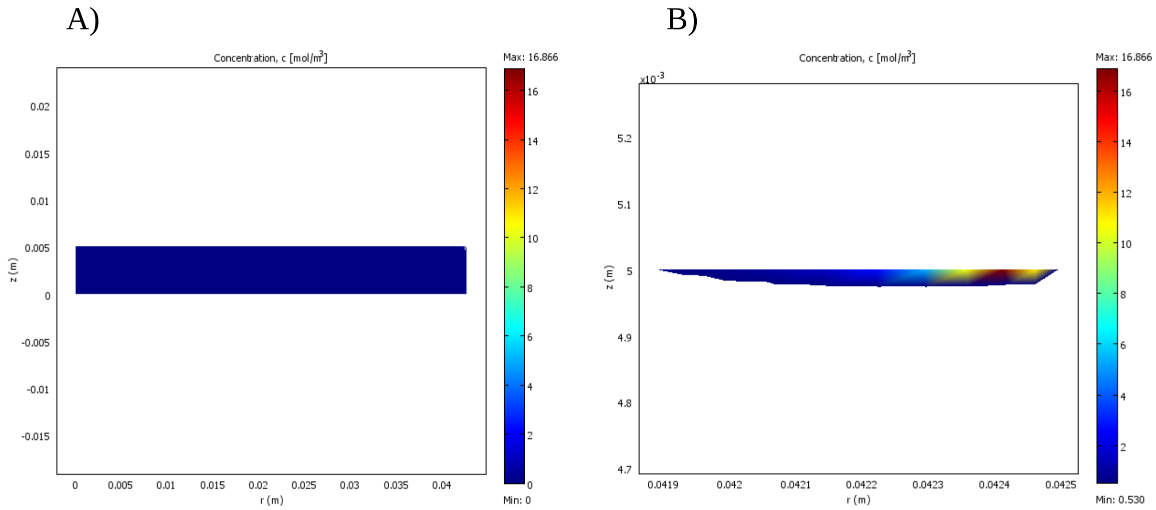

**Figure 5:** The above concentration profile shows the amount of burn in the skin. The range of the figure was set manually to only show regions over which the burn equation represents the most necrosis at the dermis (i.e showing only regions with values greater than 0.53). (A) is the plot of burn over the dermal layer beneath the 1mm thick gel after 6 seconds. (B) is an enlarged plot dermal layer where only the regions with omega values greater than 0.53 are shown.

The above concentration profile allows us to quantify and visualize the thermal injury. Using the accepted burn threshold data, we chose to assume that values of concentration greater than 0.53 would be considered a damaging thermal injury. Because our model did predict some higher temperatures, especially in the gel region, we chose to plot the concentration of thermal injury *only* in regions where the values were greater than 0.53. Therefore, the above plot shows the thermal injury between values above 0.53, this confirms Ambler's experimental findings, and our design hypotheses.

### *Design Objective #2: Optimization of Gel Thickness*

Our second design objective was to model cardiac defibrillation to determine the ideal thickness of the applied gel. To determine the effect of gel thickness on the temperature profile in the skin layers, we ran our model with three different gel thicknesses, 0.5mm, 1.0mm, and 1.5mm. The calculated temperature and burn profiles are displayed below.

## Temperature and Burn Profiles as Gel Thickness Increases

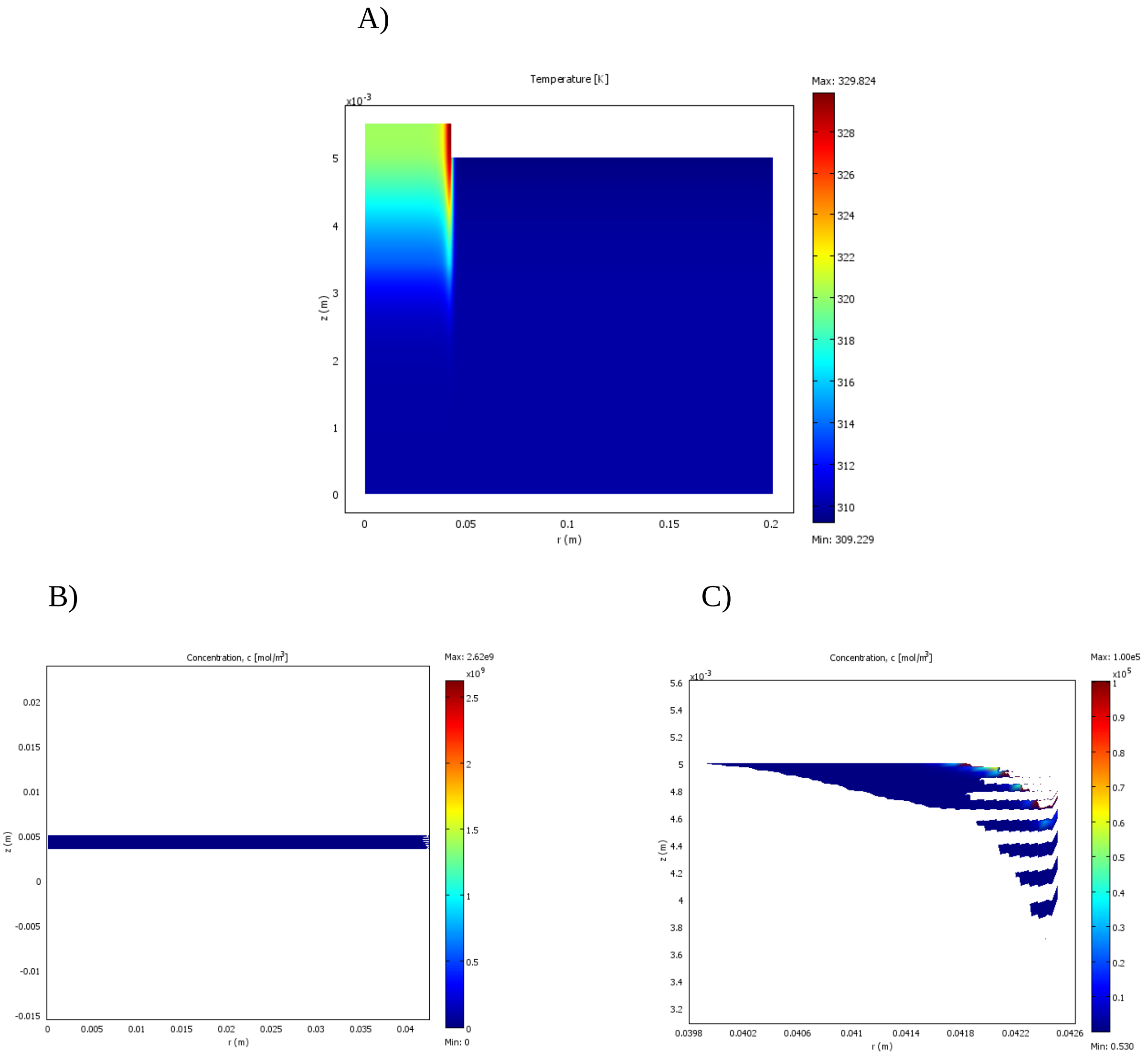

**Figure 7:** Temperature and Burn Profile with a 0.5 mm thick gel after 6 seconds. (A) is the temperature profile with a maximum temperature of 328K occurs in the epidermis. (B) shows the plot of burn over the dermal layer beneath the 0.5 mm thick gel after 6 seconds. (C) is an enlarged plot of dermal layer. Only regions with omega values greater than 0.53 are shown.

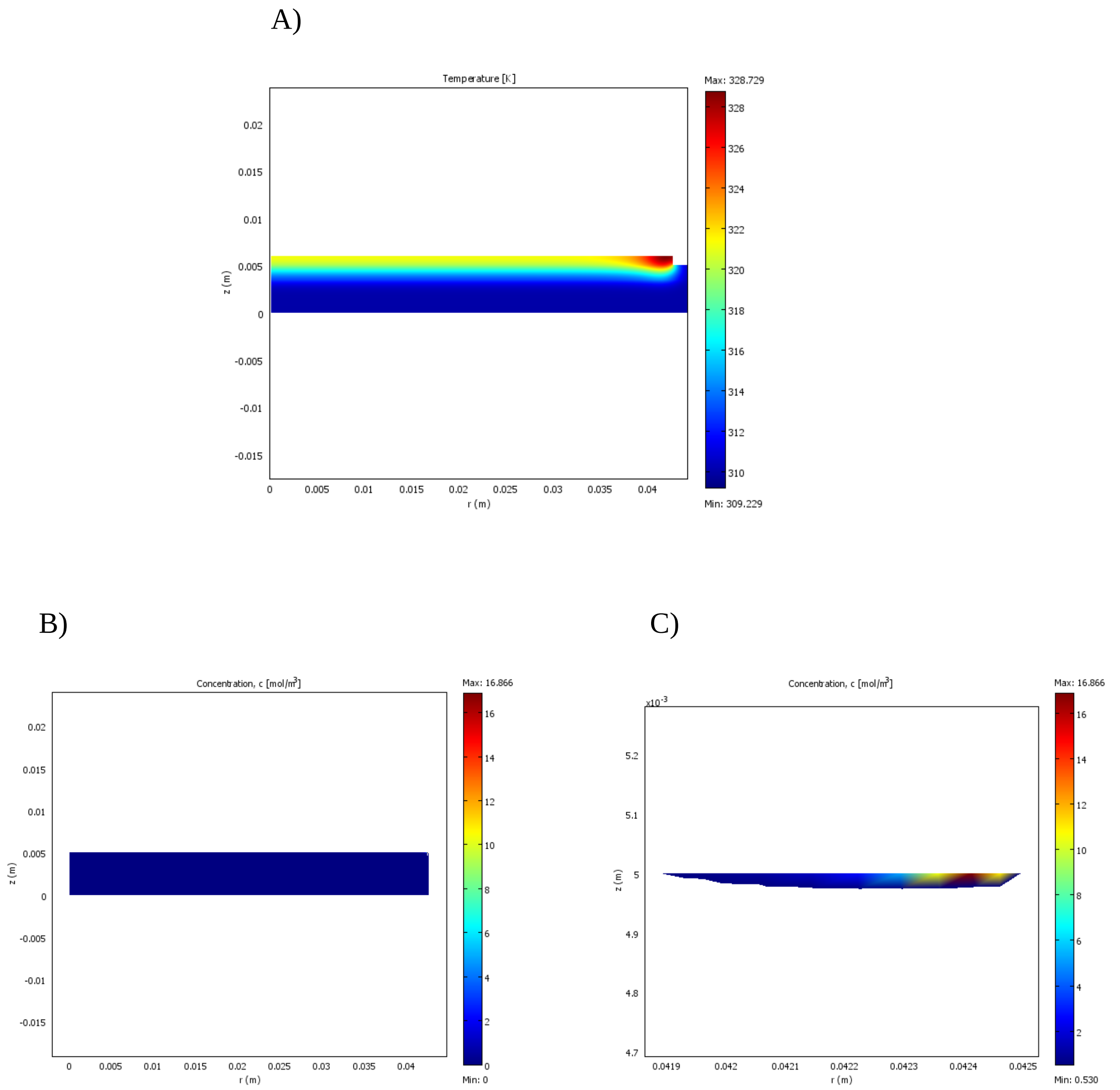

**Figure 8:** Temperature and Burn Profile with a 1 mm thick gel after 6 seconds. (A) shows the temperature profile with a 1.0 mm gel layer thickness. A maximum temperature of 322K occurs in the skin. (B) shows the plot of burn over the dermal layer beneath the gel. (C) is an enlarged plot dermal layer. Only the regions with omega values greater than 0.53 are shown.

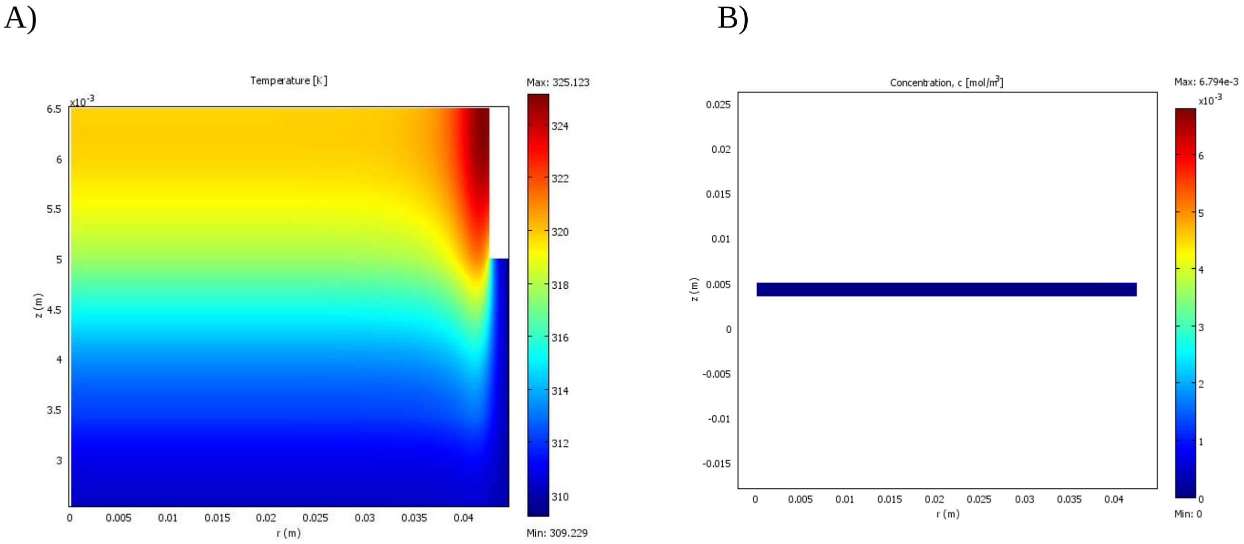

**Figure 9:** Temperature and Burn profile with a 1.5 mm gel layer thickness after 6 seconds. (A) shows a maximum temperature of 316K occurs in the skin. (B) is a plot of burn over the dermal layer beneath the gel

From the series of figures above, the gel layer thickness has a large impact on the temperature profile, such that the maximum temperatures are 328, 322K, and 316K for gel layer thicknesses of 0.5mm, 1.0mm, and 1.5mm, respectively. Additionally, the gel layer thickness has a large impact on the extent of skin burning, with burn concentration values of 1e5, 16, and 0 for gel layer thicknesses of 0.5mm, 1.0mm, and 1.5mm, respectively. Therefore, as the thickness of the gel layer increases, skin temperature and severity of the patient's burns decrease significantly.

In terms of our first objective, the COMSOL model enabled us to develop a better understanding of the phenomenon of skin burning after defibrillation. We found that first-degree burns occur in the epidermal regions beneath the paddle site. These results are confirmed by Ambler et. al. who found that skin burns were made beneath the paddle due to the use of a defibrillator.[2] For our second design objective, our results show that the gel that is placed between the defibrillator and the skin plays a critical role in the reducing this phenomenon.[3] It is evident that as the thickness of the gel is increased, the epidermal burning is drastically decreased.

## Sensitivity Analysis

In order to determine how sensitive our model was to different input parameters, we varied several key parameters over a 10% and then a 20% range and tracked the maximum temperature in the skin over these parameter variations. The five properties we chose to vary were the density, thermal conductivity, and specific heat of the dermis, the electrical conductivity of the gel, and the applied voltage of the defibrillator. These specific properties were selected because we had more uncertainty in finding these values, so we wanted to gauge how these numbers would change our results.

The results of our sensitivity analysis are shown below:

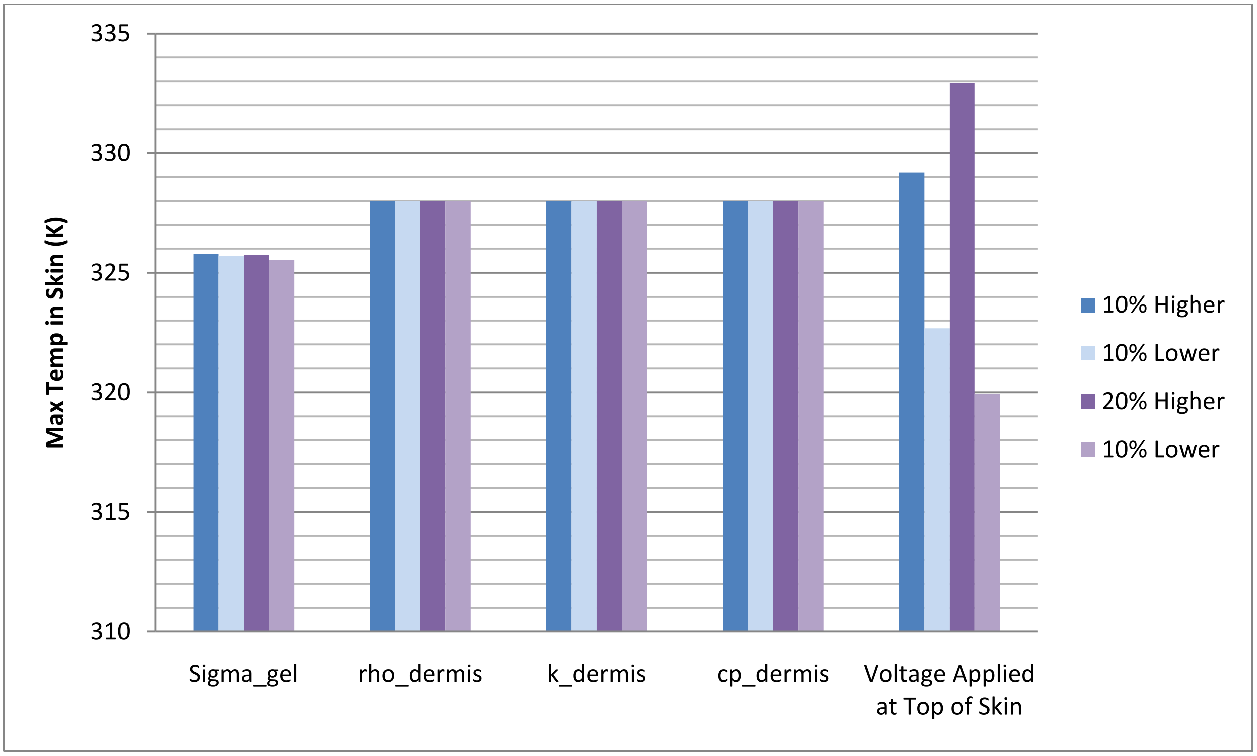

**Figure 10:** Sensitivity analysis results, showing variation of key thermal and electrical properties.

As can be seen in the above figure, it is clear that our model was not very sensitive to dermal property values. These results are as expected because the properties were rather small compared to other properties in the rest of the model. Varying the properties by 10% and 20% was not very significant because the values were so small. However, it is clear that our model was highly sensitive to the voltage applied at the top of the gel, and slightly sensitive to the electrical conductivity of the gel, meaning the accuracy of the voltage data was significantly important. Because of this, we obtained various defibrillator user manuals for defibrillators on the market today from Professor David Lipson, to obtain voltage values from these manuals themselves.[10]

### *Accuracy Check*

Although burns following defibrillation are qualitatively very common, there is a lack of quantifiable knowledge of this problem, and no modeling work was found that covered this topic. Because experiments cannot be performed easily in this area, since defibrillation is an emergency procedure, it was very difficult for us to find thorough experimental results to compare our data. However, we did find experimental data in the work of Ambler et al, mentioned in the introduction of this paper. This study did not find any statistically significant difference between the burns with the steroid cream and with the aqueous cream, as assessed by the burn quantification tests detailed in the description of the study in the introduction section.[3] This verifies that using water properties for modeling our gel layer was a valid assumption, since the water-based cream (whose main ingredient is water) resulted in the same burn effects as the topical steroid cream.

In terms of other parameters, our data was compiled from a variety of sources as can be seen in our References section. It first must be noted that a selection of the needed parameters was very difficult to achieve and for that reason, it was not possible to compare values from numerous sources to make needed accuracy checks. However, for the skin properties, these are from highly recognized sources (including Professor Datta's text) and these properties should be the most accurate in the model. On the other hand, for the voltage values, there is a range that is selected for each patient, depending on his/her given condition.. In this way, it is very difficult to determine a definite value for the voltage applied to the skin as well as a percentage of this value for an accurate range. Gathering data from many sources, we found ranges as large as from 200-10000V, and these values depend not only on the choice of the defibrillator operator, but also the type and model of the defibrillator, the age of the patient (lower voltages are used on children, as expected), and the extent of cardiac arrest the person is experiencing. Due to this, it is very difficult to say how accurate this data is – which is why the sensitivity check was pivotal. Our choice of a voltage around 3500V[2] was on the higher end of most voltage ranges for modern defibrillators, since voltages above 3500V are typically only found in older defibrillators that are no longer in use today (and all the sources that cited higher voltage ranges that went up to 10000V confirmed that these values were for much older defibrillators that are not comparable to the defibrillators we were trying to model). We confirmed our choice of 3500V using the defibrillator user manuals obtained from Professor Lipson[10], and so we did all we could to validate the accuracy of this value since our model was highly sensitive to it.

## Conclusion

Our objectives were to assess the burning of the skin following defibrillation, and to determine the reduction in burning by optimizing the thickness of the applied gel. Looking at the results generated by our model, we have various temperature, voltage, and burn profiles throughout the different layers on the skin that can be used to better quantify the problem. It is clear that we were able to satisfy our first objective, since our results prove that burning does occur in epidermal regions, and these results are discussed in previous sections of this report. For our second objective, we were able to successfully show that increasing the thickness of the gel layer did indeed decrease the temperature and burn profiles in the skin, suggesting that our hypothesis was correct. Our informed recommendation based on the results of our model is thus to apply a thicker gel layer to the chest prior to defibrillation in order to minimize the burning occurring in the epidermal and dermal layers of the skin.

### *Design Recommendations*

If we were to continue research into this modeling work, we would recommend several adjustments to make the model more adaptable and accurate. The first would be to somehow be able to quantify age, skin type, and extent of cardiac arrest so that they could be included as parameters in the model. This would make the model versatile enough to account for many different defibrillation situations. Another recommendation would be to include the internal organs, tissue, and fluid in the body between the hypodermis and the heart in the model. Our model's focus was on the skin, and so in terms of efficiency with the time we had, we had to make the model simple enough to get reasonably accurate dermal burning data, but future work should include the region between the skin and heart in a model, since it would make the model highly accurate (though very time-consuming to run multiple times).

### *Realistic Constraints*

In terms of whether the implementation of our design problem is realistic, the answer is yes, but with some limitations. Although it seems easy enough to apply a thicker layer of gel to a patient prior to defibrillation, it is important to understand that in a "real-life" setting, defibrillation is an emergency procedure where every second counts. There is no time to measure out an accepted amount of gel or apply the gel in such a way that it is uniformly thick because each second wasted is the difference between life and death. The priority in defibrillating a patient is first and foremost to revive the patient's heart – cutaneous burning is an unfortunate side effect that cannot be considered a top priority. However, there are ways to incorporate the results of our model into the real world. For example, many electrodes now come pre-manufactured, with layers of gel built in to the electrodes[9]. Modifying the thickness of the gel layers in the manufacturing stage would be a much simpler process than changing the application of gel in a life-or-death situation. Medical device companies would simply have to change their specifications of gel thickness to a more appropriate value, which could be determined by running more simple model-based simulations such as the one in this report. Overall, we found that our hypothesis was correct and that our findings have the potential to be implemented in real defibrillators, with relatively little cost to the companies manufacturing them.

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9. “Medical Electrode Method of Manufacture”. Axelgaard, Jens et all. US Patent Number 6,198,955 B1. Issued 6 Mar 2001. Filed 29 Sep 1999.
10. Medtronic LifePak 500 Automated External Defibrillator Operating Instructions and User Manuals (obtained with permission from Medtronic through Professor David Lipson).

## Appendix A

### Governing Equations

Two Dimensional Energy Conservation Equations in Cylindrical Coordinates (Heat Transfer Equation):

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

No Convection, therefore:

$$\left(v_r \frac{\partial T}{\partial r} + v_z \frac{\partial T}{\partial z}\right) = 0$$

Heat generation is related to:

$$Q = \sigma \, |\nabla V|^2$$

We will model this source term using COMSOL's conductive media DC function, and so Q in the gel layer will be equal to Q_dc.

Final Equation:

$$\boxed{\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right) + \sigma \, |\nabla V|^2}$$

The degree of tissue injury, **Ω**, due to heating is given by the following equation developed by Henriques and Moritz (1947):

$$\frac{d\Omega}{dt} = Aexp(-\frac{\Delta E}{RT})$$

Where A is defined as the frequency factor, $\Delta E$ as the activation energy and R as the universal gas constant. This was implemented in COMSOL via the diffusion equation application shown below.

$$\delta_{ts}\frac{dc}{dt} + \nabla \cdot (-D\nabla c) = R$$

Within this equation, D is set to 0, $\delta_{ts}$ = 1, and R is set to 3e98*exp(-6.3e8/(8.314e3*T)).

### *Boundary Conditions*

| **Parameter** | **Value** |
|---|---|
| Voltage BCs: | |
| Voltage at Heart = Voltage at Bottom Skin Layer | 30V (applied as time-varying for 1 ms) |
| Applied Voltage = Voltage at Top Layer | 3500V (applied as time-varying for 1ms) |
| All other sides | Electric Insulation |
| Temperature BCs | |
| Top of gel and top of skin | Heat Flux |
| Bottom | T = 37°C (body temp) |
| Right side | T = 37°C (body temp) (semi-infinite) |
| Left side | Assumed axisymmetric |
| Diffusion BCs | |
| All sides excluding axisymmetry | Insulation/symmetry |
| A | 3.00E+98 |
| ΔE | -6.30E+08 |
| R | 8.31E+03 |

**Table 1:** Boundary Condition Values

## Appendix B

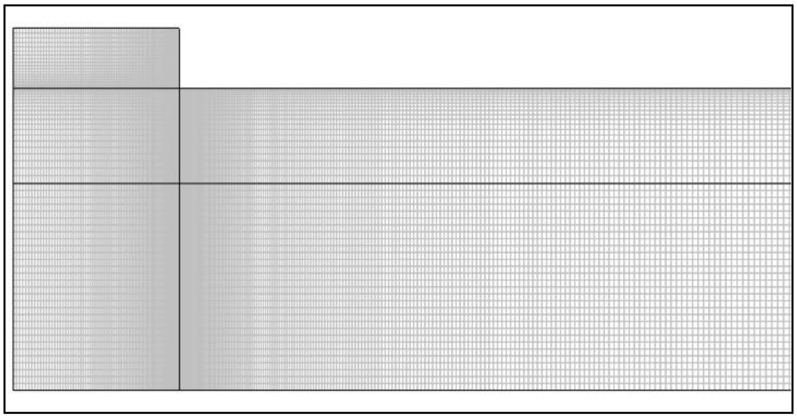

**Figure 11:** Mapped Mesh

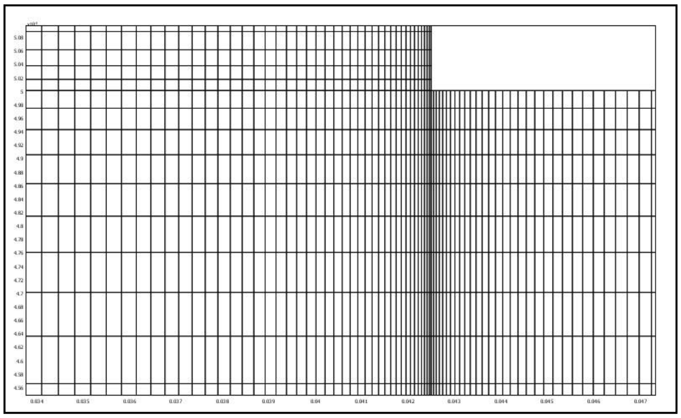

**Figure 12:** Zoomed Mesh

Mesh convergence was studied by recording the maximum temperature within the skin (dermis and subcutaneous fat layers). We successively increased the number of edge elements in the mapped mesh parameters until we reached a convergent solution. We changed both the number of elements in the vertical and horizontal directions, and because of our geometry we saw large changes in temperature when increasing the number of elements along the r-axis (horizontally). We divided the geometry as shown in Figure 17 in order to achieve a more accurate mapped mesh. It doesn't add any physical meaning – only assists in computation. In addition, more elements are placed by the edge of the defibrillator where the ring burns occur. As can be seen below, the mesh started to converge at around 17,000 elements. Therefore, to solve the problem we will only need to use a mesh size of around 17,000 elements to still have a viable solution.

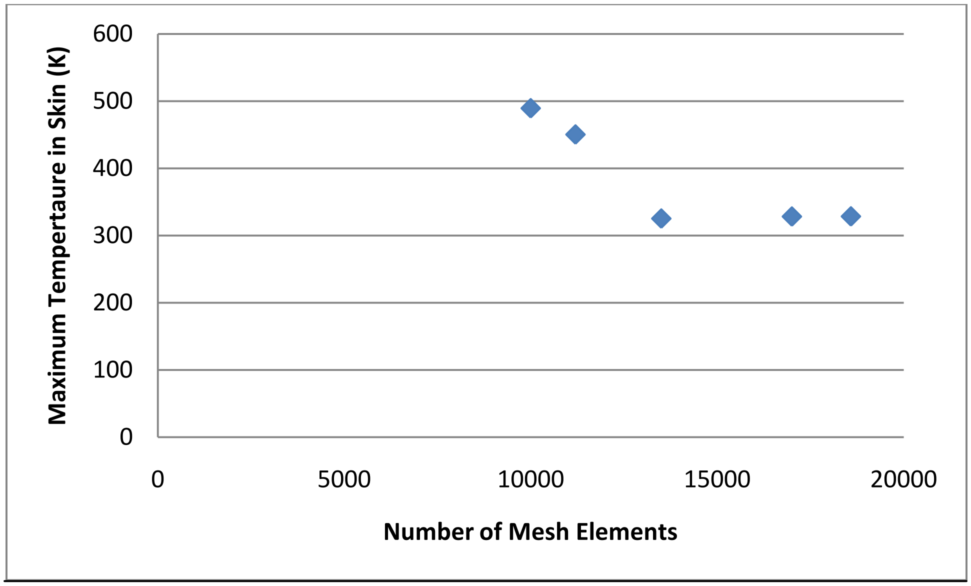

**Figure 13:** Mesh Convergence Analysis

## Appendix C

Parameters

| | **Thickness(m)** | **K (W/mK)** | **Cp (J/kgK)** | **Density (kg/m3)** | **Electrical conductivity (S m-1)** | **Q** |
|---|---|---|---|---|---|---|
| **Skin:** | | | | | | |
| **Epidermis** | .000075 | .21 | 3181.82 | 1000 | .001429 | |
| **Dermis** | .0015 | .37 | 2846.15 | 1000 | .001429 | |
| **Subcutaneous Fat** | .003425 | .16 | 1975.31 | 1000 | .001429 | |
| | | | | | | |
| **Gel** | .001 | .58 | 4180 | 1000 | .0005 | Q_dc |

**Table 2:** Properties of Each Layer[4,5,6,7]