

# Modeling the Effects of Induced Hypothermia for the Treatment of a Cervical Spinal Cord Injury

BEE 4530: Computer-Aided Engineering

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## 1. Executive Summary

Spinal cord injury (SCI) is a devastating condition that affects approximately 11,000 patients each year in the United States. Moderate hypothermia has been used in a variety of experimental and clinical situations to target several neurological disorders, including traumatic brain injury and SCI. Studies in a large series of SCI patients, initiated in 2005, showed that early cooling introduced by the use of endovascular catheters and continued for a 48-hour period appeared to be safe and did not result in an increased incidence of risk factors, including cardiac arrhythmias and severe infection. However, the procedure for inserting endovascular catheters is invasive, which can be detrimental to the patient. Prolonged systemic hypothermia in patients can also lead to further complications, such as tissue damage due to frostbite. As a result, less invasive local methodologies are being explored and studied to determine if the results of cooling are comparably effective or superior to systemic hypothermic treatment. The goal of this project was to model induced temperatures at or below 33°C (306 K) in the spinal cord through localized surface cooling via a cooling pack in COMSOL Multiphysics.

Through the development and execution of an accurate model, we determined the amount of time the cooling pack must be applied, the temperature the body must be cooled down to, and the long-term cooling pack application protocol needed to maintain critical temperatures in the spinal cord while preventing frostbite in surface tissues. A schematic of a simplified geometry of the cross-section of the neck was created. Only half of the geometry was needed for the schematic of the model as a result of simplification due to symmetry. It included regions for the skin, neck tissue, vasculature, vertebral bone, and spinal cord (target) and was run in 2-D. COMSOL was utilized to solve for transient heat transfer in cylindrical coordinates with a conduction term and two sources of heat generation representing base metabolism and inflammation. We expected to find that the application of the cooling pack would decrease the core temperature from 37°C to 33°C (310 K to 306 K), which is the temperature systemic cooling range for current therapeutic use.

Initially, the model was run with constant application of the cooling pack. We determined that the cooling pack was capable of lowering the spinal cord temperature to 21°C (294 K) over the course of three hours. However, constant application of the cooling pack led to

tissue degradation due to frostbite. To avoid frostbite, we attempted to create a cyclic application protocol that would maintain temperatures below 33°C (306 K) in the spinal cord while preventing the surrounding tissues from reaching freezing temperatures of 0°C (273 K). We found that the most effective protocol consisted of initially applying the cooling pack for 30 minutes at 0°C (273 K), removing the cooling pad, heating the neck for 30 minutes at 37°C (310 K), and then cyclically cooling for 20 minutes and heating for 30 minutes thereafter. We found that the spinal cord temperature reached 33°C (306 K) in less than 45 minutes and subsequently fluctuated stably between 30°C – 31°C (303 K – 304 K). Also, tissue temperatures were found to be stay above freezing, fluctuating between 2.5°C – 37°C (275.5 K – 310 K). An accuracy check was executed to ensure that our solutions were comparable to the results of analogous experiments. We performed sensitivity analysis of the temperature change in the spine to different heat generation terms and various parameters in the skin, tissue, bone, and spine and found that the model was relatively insensitive to these changes. The results of the sensitivity analysis implied that the model was robust to changes in parameter values.

The significance of this data demonstrated that hypothermia could be successfully induced with the application of a cooling pack alone, preventing the need for invasive systemic cooling procedures. The ability to induce spinal cord cooling without insertion of cooling catheters is a significant advancement due to the fact that significant systemic hypothermia (< 33°C, < 306 K) can result in cardiac arrhythmia, coagulopathy, and pancreatitis, among other conditions. Therefore, by allowing the systemic temperature to remain at physiologically normal temperatures during cooling, physicians can further prevent many of these fatal complications through this cyclic application of a cooling pad. Finally, the development of a protocol to prevent frostbite in the local tissues while keeping the spinal cord below the therapeutic temperature of 33°C (306 K) prevents the major complication associated with local cooling. The cooling pack system can potentially be implemented by doctors in the future to induce localized cooling in SCI patients with relatively rapid results without the risk of frostbite.

## 2. Introduction

### *i. Background*

The first account of systemic hypothermia was made in November of 1938 by Dr. Temple Fay, MD, FACS [1]. Dr. Fay's first description of intentionally induced hypothermia was actually an attempt to slow the progression of metastatic disease in a woman with ulcerating breast carcinoma. This carcinoma had previously shown "remarkable response" to local refrigeration of the breast and neck area. Fay *et al.* subsequently went on to describe the use of hypothermia in a large number of patients with cancer and head injury [2, 3]. The idea of using hypothermia in cardiac surgery was introduced by Bigelow *et al.* after a series of canine experiments [4]. In addition, Botterell *et al.* began pioneering work in the use of hypothermia in cerebral aneurysm repair in the 1950s [5]. As a result, hypothermia was defined to occur between the temperatures, 24°C and 33°C (297 K and 306 K). Enthusiasm towards induced hypothermia dwindled in the subsequent decades, and was largely abandoned by the 1980s. This disinterest was largely attributed to the associated complications, which included cardiac arrhythmias, hypotension, coagulopathies, systemic infections, and electrolyte disturbances [6]. In 1987, Busto *et al.* documented that neuronal injury could be markedly attenuated by modest decreases in body temperatures in a rat model of global ischemia. This suggested that the extent of hypothermia required for neuroprotection was not as pronounced as initially anticipated [7]. Consequently, there was a renewed interest in hypothermia. The degree of hypothermia was loosely defined by ranges of temperature as "mild" (33°C – 36°C), "moderate" (28°C – 32°C), "severe" (16°C – 28°C), and "profound" (15°C and below) [8]. The specifications of the levels of hypothermia were important because of the potential for neurologic benefit with more modest reductions in body temperatures. Due to its newly discovered applicability, mild to moderate hypothermia has attracted more interest over the past two decades. It has been very effective in acute traumatic brain injury, spinal cord injury, stroke, cardiac surgery, surgical repair of cerebral aneurysms, and thoracoabdominal aortic aneurysm (TAA) [6, 9].

Localized cooling of the spinal cord can be achieved either externally by surface cooling or internally via endovascular cooling [10]. Our study concentrated on achieving localized hypothermia by external surface cooling, which is noninvasive and, therefore, a more appealing procedure. Surface cooling systems, which use the circulation of cool air or water through

devices that are placed against the skin, have been made popular because of their ease of use. These systems include the Bair Hugger System and Arizant Healthcare Inc. Systemic Hypothermia. As used currently, both usually target a temperature between 32°C and 34°C (305 K and 307 K). These temperatures are less prone to severe adverse effects, such as arrhythmias, than temperatures below 30°C (303 K). For our project, we aimed to lower the temperature of the spinal cord to 33°C (306 K).

The goal of this project was to model localized cooling in the treatment of injuries to the cervical spinal cord using COMSOL Multiphysics. The model was developed to demonstrate the efficiency and effects of the application of a cooling pack to the surface of the neck on the temperature of the spinal cord. This model involved the transfer of heat through four layers (skin, tissue, vertebral bone, and spinal cord), which each exhibit different material properties. Our model can ultimately create efficient and safe guidelines to inducing localized hypothermia through the analysis of the extent of temperature changes, the time in which those changes occur, and the sensitivity of the model to different parameters.

This report will provide the reader with the procedure of the analysis of this model utilizing COMSOL, beginning with the governing equation and boundary conditions of this particular model. The core vasculature was kept at a constant body temperature of 37°C (310 K). The model included the results of the application of an ice pack kept at a constant temperature to the surface of the neck, as well as the results of alternating cooling and heating cycles. In order to perform an accuracy check, we created an analogous model to a paper that studied localized cooling of the spinal cord of rats and compared the results. Sensitivity analysis of the model was performed to demonstrate the effects of changing the heat generation term and various parameters of the skin, tissue, bone, and spine on the results. The analysis of the results determined that the tissues were kept at temperatures above freezing, the temperature of the spine was below 33 °C (306 K), and the length of time needed for effective and successful application of the cooling pack.

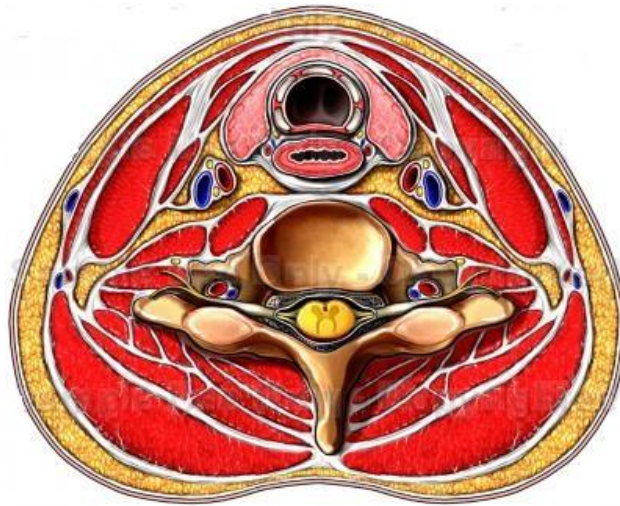
## *ii. Design Objectives*

Given that our focus is to establish the conditions of induced hypothermia in neck injury patients, our main objectives are:

- Determine how long it will take for the temperature of the core region to reach  $33^{\circ}\text{C}$  (306 K) [11]
- Determine what the systemic temperature needs to be to allow for a stable decrease to  $33^{\circ}\text{C}$  (306 K) in the spinal cord
- Determine a cooling pack application protocol that allows the injury site temperature to remain below  $33^{\circ}\text{C}$  (306 K) while ensuring local tissues remain above  $0^{\circ}\text{C}$  (273 K)

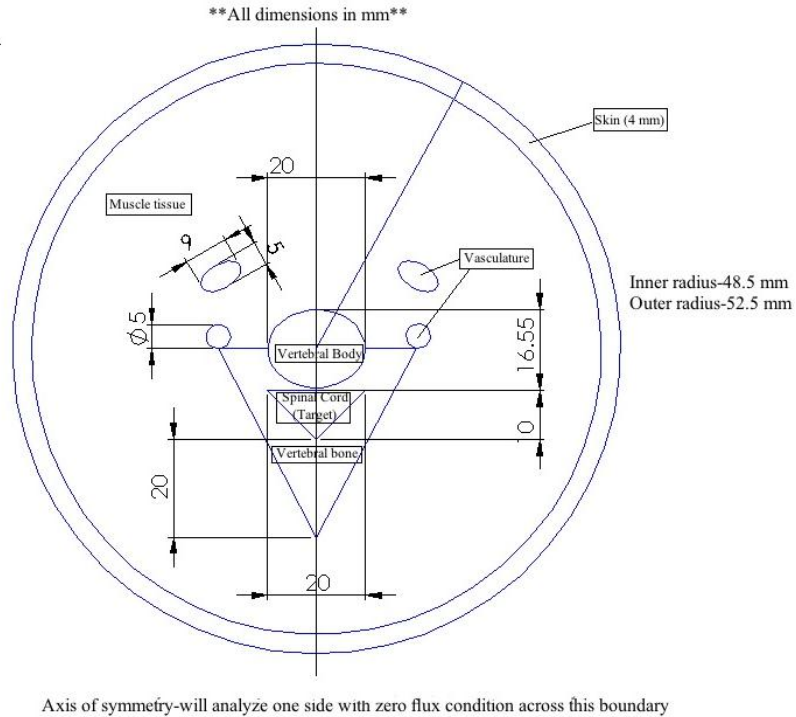
## *iii. Problem Schematic*

The most common injury to the spinal cord occurs at the C3-C4 junction. This is also the highest spinal cord injury that has outcomes that allow for positive outcomes, as most injuries above C3 are fatal or result in required ventilator use since control of the diaphragm is lost [12]. Thus, we decided to first look for a cross-section of the neck at this location to serve as a basis of our model.



**Figure 1: Picture of a cross section of neck.** The above is a photo of a cross section of the neck including local vasculature, particularly relevant in this case, the spine.

After finding the above schematic, we simplified the physiology to allow for modeling in COMSOL. Ultimately, we decided to preserve the skin/fat layer, general tissues, vertebral bone, major vasculature, and spinal cord sections.



**Figure 2: Simplified schematic of a neck cross-section.** The above schematic, which was redrawn in COMSOL, is a simplified version of the cross section in Figure 1, only including relevant vasculature.

Geometries in the above schematic were based on measurements taken from the original cross section schematic and the dimensional work of Gilad and Nissan [13].

Boundary Conditions:

$$T(r = R) = T(\text{cooling pack}), \text{ where } R \text{ is at the surface.}$$

Initial Conditions:

$$T_{\text{body}}(t = 0) = 37^{\circ}\text{C} = 310 \text{ K}$$



Other parameters:

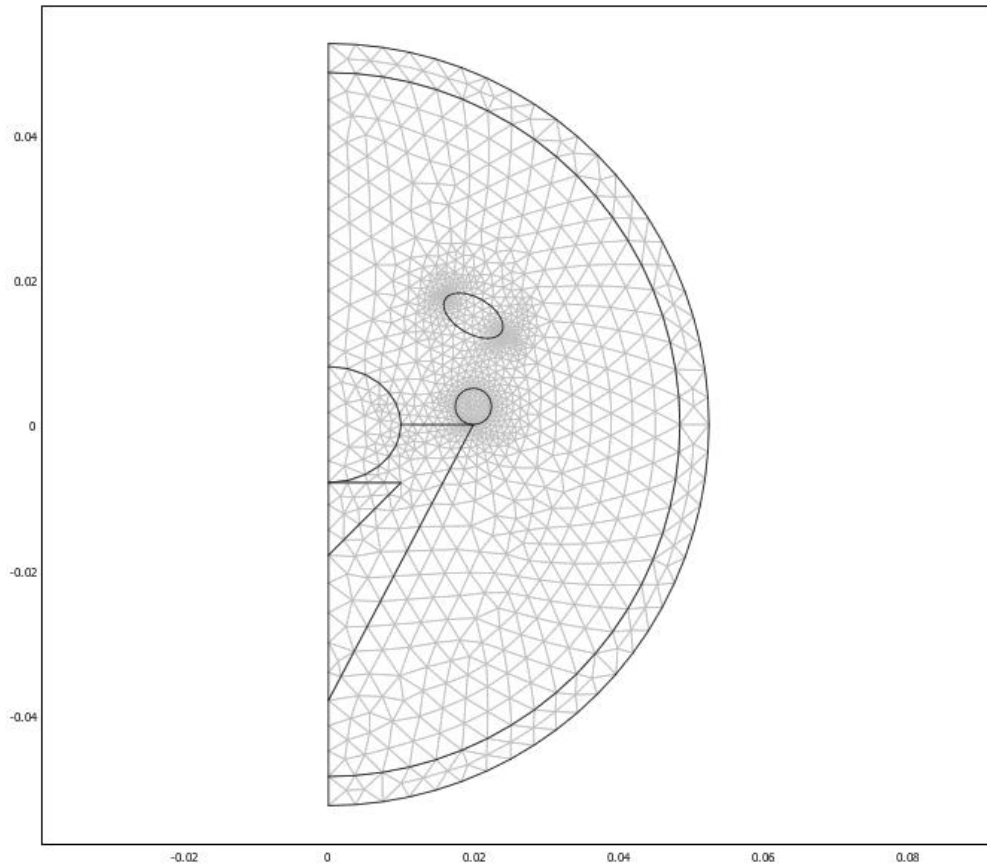
In order to run the model, heat transfer properties had to be determined for all the involved tissues. Table 1 displays the values used for the various tissues.

**Table 1:** The density, heat capacity, and conductivity values were found for the skin, tissue, and bone for the implementation of the parameters in COMSOL.

<b>Properties</b>	<b>Skin</b> <sup>1,2</sup>	<b>Tissue</b> <sup>3,4</sup>	<b>Bone</b> <sup>5,6,7</sup>
<b>Density</b>	1200 kg m <sup>3</sup>	1020 kg m <sup>3</sup>	1500 kg m <sup>3</sup>
<b>Capacity</b>	3600 J kg <sup>-1</sup> K <sup>-1</sup>	3558 J kg <sup>-1</sup> K <sup>-1</sup>	440 J kg <sup>-1</sup> K <sup>-1</sup>
<b>Conductivity</b>	0.53 W m <sup>-1</sup> K <sup>-1</sup>	0.21 W m <sup>-1</sup> K <sup>-1</sup>	0.25 W m <sup>-1</sup> °C

*iv. Mesh*

In order to utilize the simplified schematic seen in Figure 2 in COMSOL, a mesh was created. The symmetry of the model allowed for further simplification of the schematic to only include half of the cross section. This mesh included 2328 elements, which were used in a fine mesh.

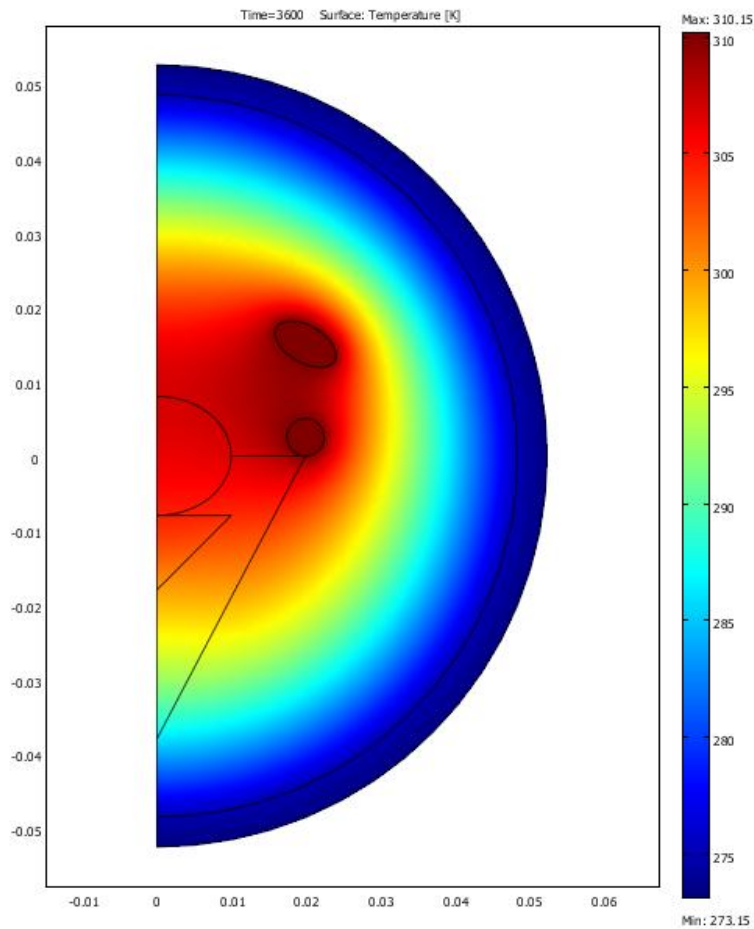


**Figure 3: Mesh of the simplified schematic.** Above is the mesh used in the modeling of the simplified schematic of Figure 2. Symmetry allowed only half of the simplified schematic to be modeled with the line of symmetry through the vertical axis. This figure shows a fine mesh using 2328 elements.

Once the mesh was in place, COMSOL was implemented to determine the distribution of temperature within the neck cross section after cooling had taken place.

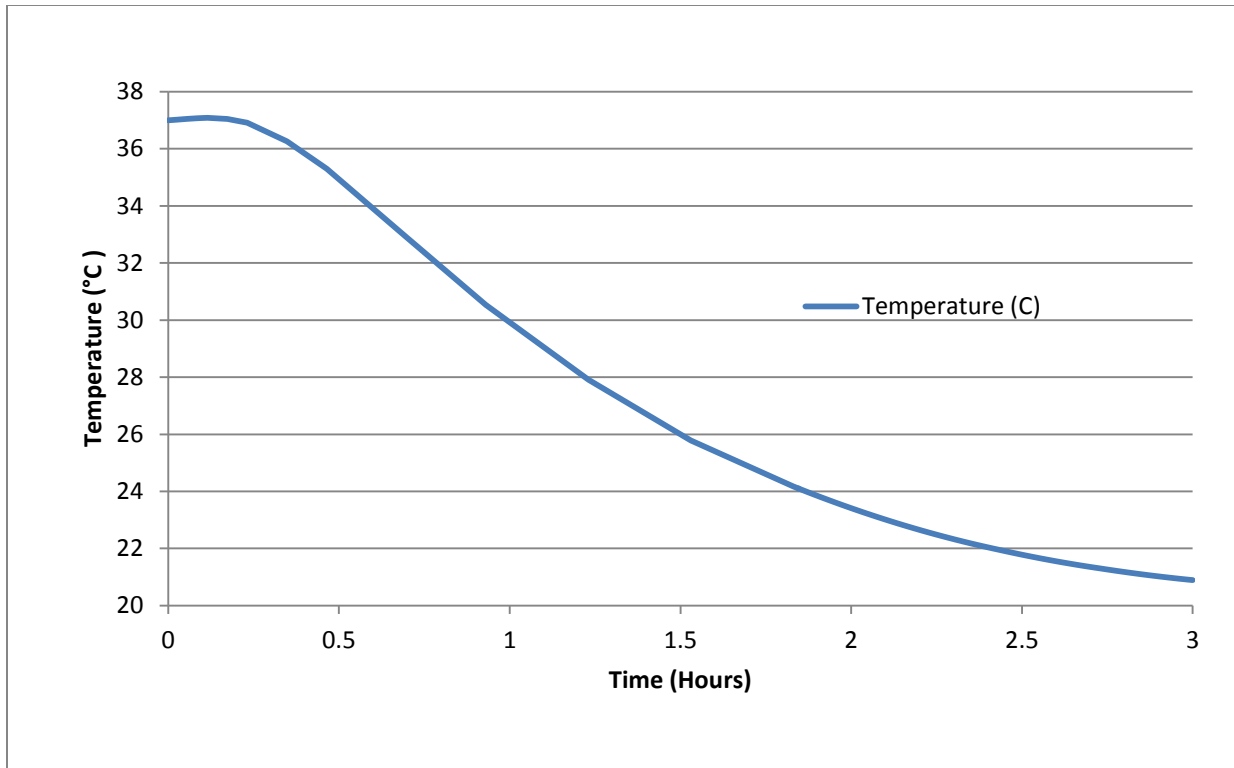
## Results and Discussion

### *i. Solution Analysis*



**Figure 4: Temperature Contour Plot of the Neck Cross Section.** Above is the temperature distribution of the neck schematic after 1 hour of ice pack application. The data of this graph includes the generation terms of the governing equation as applicable for 1 hour.

The temperature contour plot shows that the temperature throughout the cross section changed from the initial temperature of  $37^{\circ}\text{C}$  (310 K). In order to further analyze this change, the temperature change within the target area, the spine, was plotted versus time for the time span of cooling.

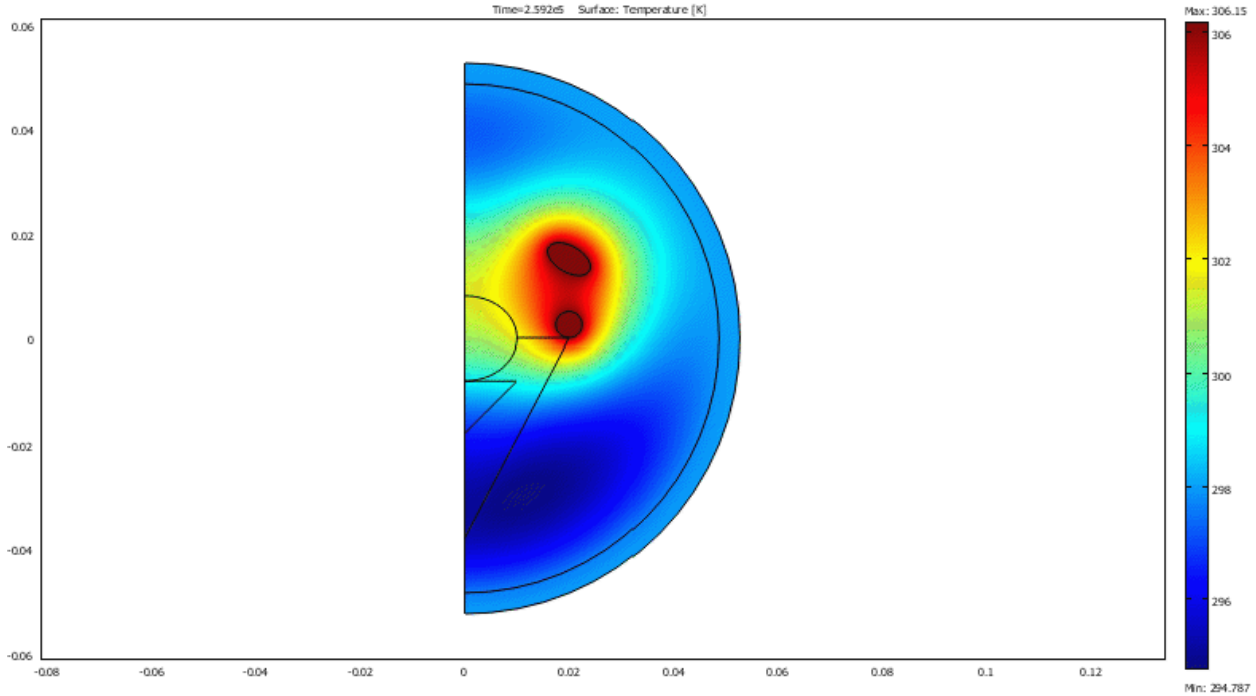


**Figure 5: Temperature vs. Time Graph of Neck Schematic.** The above graph shows the change in temperature with increasing time in the spinal column at point (0,-0.0125). The graph shows a decrease in temperature at the particular point from 37°C (310 K) to the target temperature of 33°C (306 K) in less than 45 minutes of cooling time. The data of this graph includes the generation terms of the governing

It can be seen in Figure 5 that the spine was significantly cooled during a cooling time of 3 hours. While it began at the initial temperature of 37°C (310 K), the temperature at point (0, -0.0125), representing the center of the spine, decreased to the target temperature of 33°C (306 K) in less than 45 minutes.

While lowering the temperature of the spinal cord to the target 33°C (306 K) in a timely manner is very important, it is equally important to be able to safely maintain this temperature over a longer period of time. While continuous application of the cooling pack would allow the temperature to remain well below this critical value, over time, tissues near the interface would be in danger of frostbite, a condition that occurs when tissues reach their freezing point. In order to ensure the safety of these tissues then, the cooling pack must be periodically applied and removed so as to allow for surface tissues to reheat. After several trials, we discovered that after

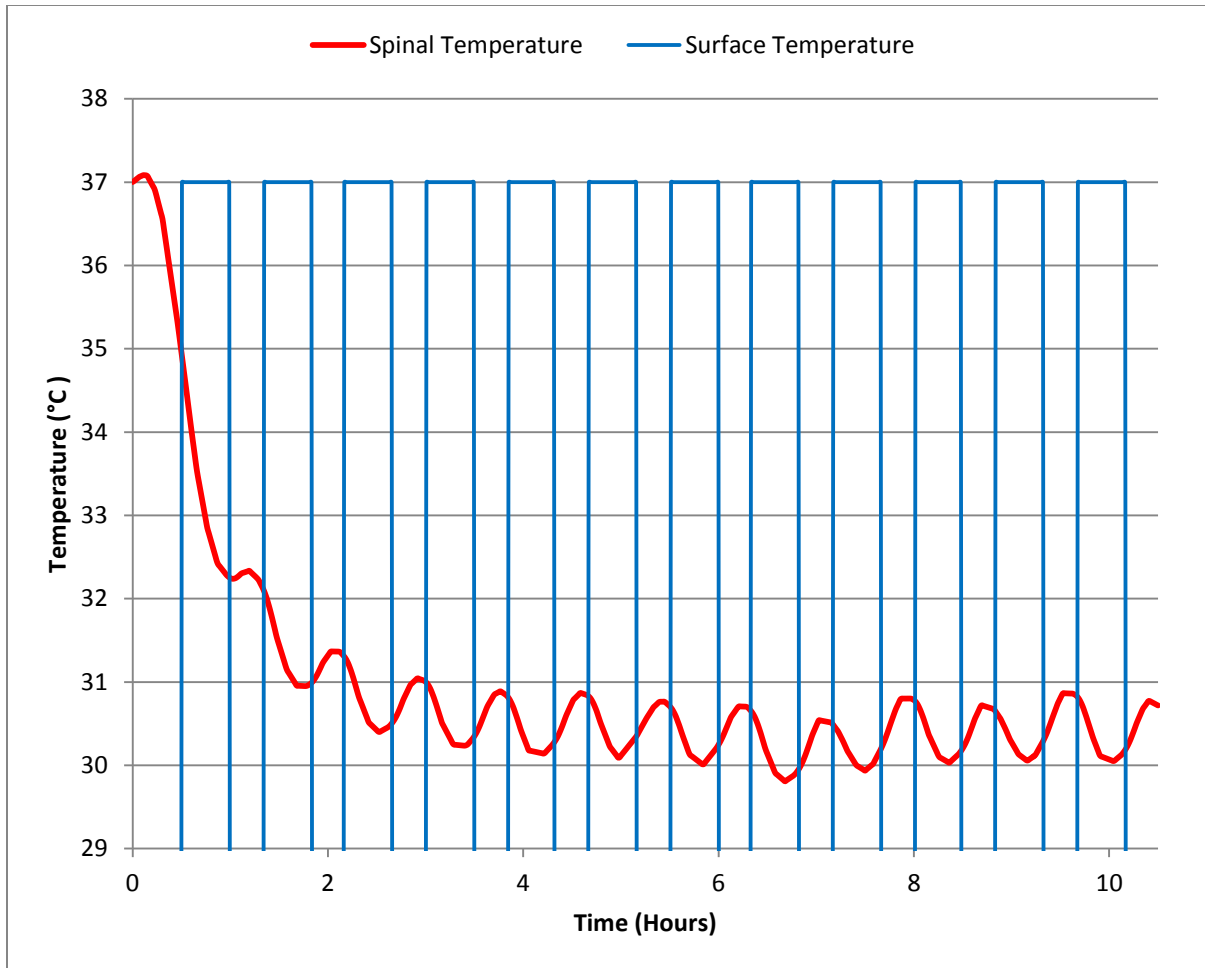
application of the cooling pad for one hour initially, continuous cycles in which the pad is removed for an hour and applied for a half hour result in a temperature profile within the tissues that allows for sufficient cooling over a long period of time, including up to 72 hours (Figure 7).



**Figure 7: Piecewise fluctuation function graph.** The above figure shows the variation in temperature when the schematic was modeled with a piecewise fluctuation function.

The fact that at 72 hours the temperatures in the skin are above those inherent in frostbite and the temperatures in the spinal cord are below the critical temperature of 33°C (306 K) suggests that this protocol is effective over a long treatment period.

However, it is important to examine the temperatures in the aforementioned tissues over the entire time period to ensure the safety of the protocol. Using this application protocol not only ensures that the spinal cord stay below the target temperature of 33°C (306 K), but also causes the temperatures within the spinal cord to fluctuate in a predictable and controlled manner from approximately 26 C to 28 C (299 K to 301 K) over an extended time period (Figure 8).

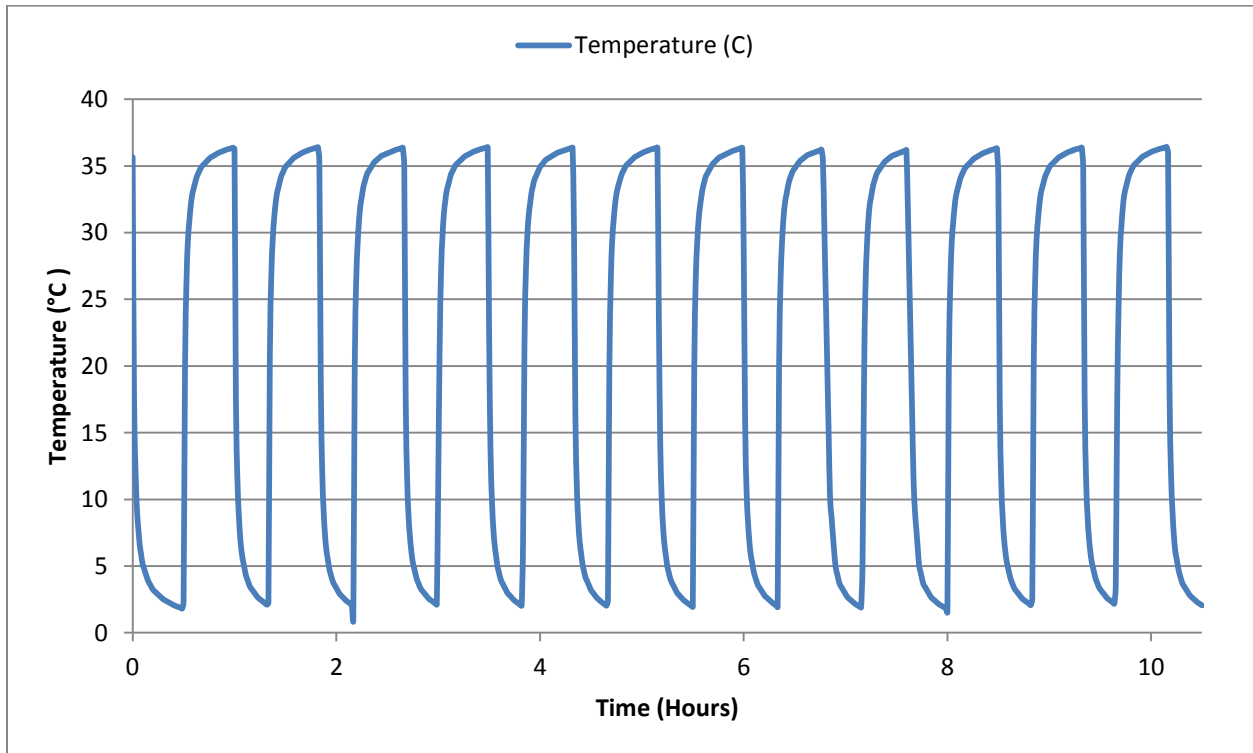


**Figure 8: Temperature versus time in the spinal column.** The above graph shows the cyclic change in temperature with regard to time in the spinal column at point (0, -0.0125). The boundary condition temperature is also plotted as a function of time (30 minutes of heating at 37 °C (310 K) followed by 20 minutes of cooling at 0°C (273 K).

This predictable fluctuation in temperature allows for greater control over the treatment of the patient and increased knowledge of the state of the injury site. Such control and information is critical in the event that emergency intervention is required at the site.

This protocol also successfully prevents the outermost tissue layer (skin) from reaching temperatures low enough for long enough to allow frostbite to occur throughout the entire duration of the protocol. As demonstrated in Figure 9, skin temperatures fluctuate regularly

between approximately 2°C (275 K) and 25°C (298 K), both of which are above freezing (0°C, 273 K).



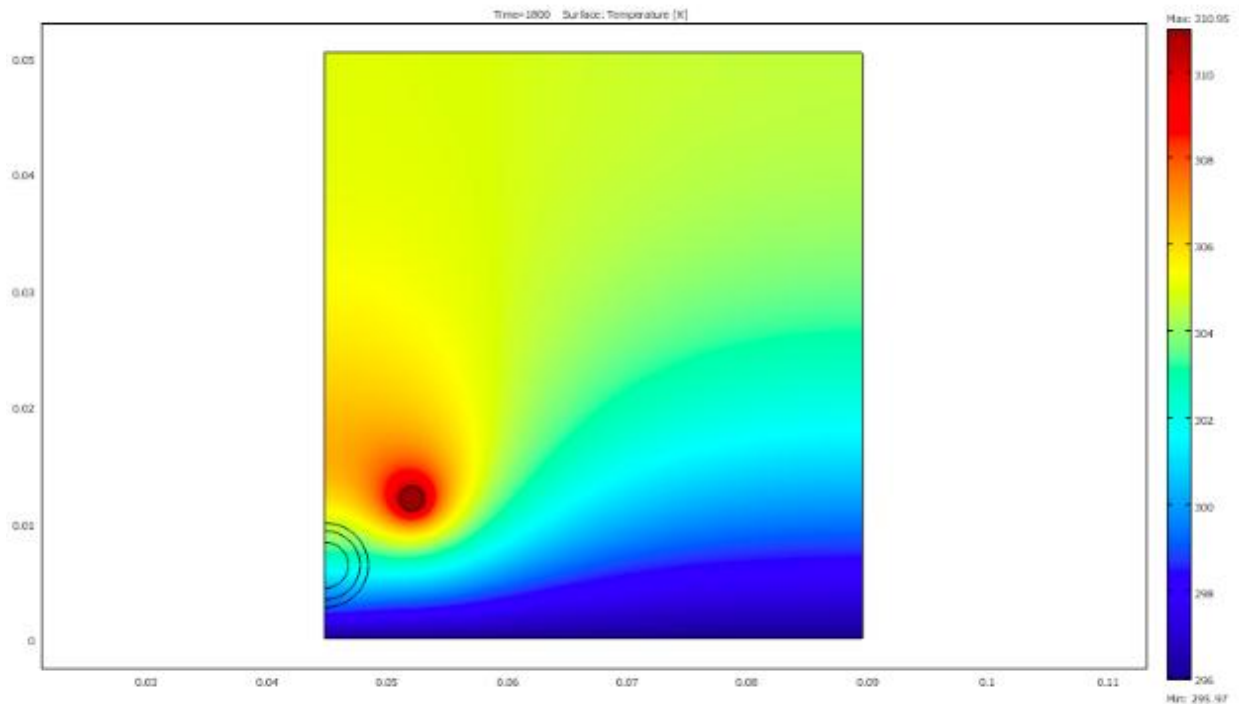
**Figure 9: Temperature vs time at skin surface.** The figure above shows the temperature versus time graph of the skin when doing fluctuating cooling.

Furthermore, while the skin does eventually reach a temperature of 2°C (275 K), which is close to 0°C (273 K), it is only at this temperature for an extremely short period of time, which further discourages the formation of frostbite. The tissue actually spends far more time at the comfortable condition of room temperature (25°C, 298K) than it does in this danger region. Thus, this application protocol not only allows the spinal cord to be kept at a sufficiently low temperature, but also allows for the protection of tissues from frostbite.

#### *ii. Accuracy Check*

Ideally, to check the accuracy of the COMSOL model, the outputs could be compared with data obtained from an in vivo experiment where humans have their spinal cords cooled by local cooling techniques. Unfortunately, this data is unavailable as such studies have not been run at this time. However, while this data is not available, in vivo data for the cooling of the

spinal cord in animals is available. Smith (2011) used a cooling blanket to reduce the spinal cord temperature in rats [21]. A cooling pad held at a constant 22.82°C (mild cooling condition) or 13.66°C (moderate cooling condition) was applied to the back of the rats directly above the spinal column for a thirty minute period. The temperature in the spinal cord was monitored over this time period through the use of a temperature probe. After a thirty minute period, the temperature in the spinal column was reduced by 6.67 and 11.89 degrees for the mild and moderate cooling conditions, respectively. Before the *in vivo* experiment, the researchers created a model that used a perfusion model to account for the effects of heating due to blood in the vasculature. To test the accuracy of our physiological simplifications, we created a rat model using the same geometric simplifications used in our human model (major tissue layers are skin, muscle, bone, and spinal tissue with normalized shapes) to compare with the experimental results. In both our models we also accounted for the effect of the blood in the vasculature by modeling the major arteries as constant temperature geometric figures (Figure 10).



**Figure 10: Temperature Contour Plot of Rat Torso.** Temperature profile for rat torso and spinal column after thirty minutes of mild cooling (22.82°C). Note that the temperature of the vasculature remains at physiological normal while the surrounding tissues drop.



We felt this was a reasonable assumption, as core temperature should remain relatively constant with localized cooling and this core temperature should sufficiently heat the blood as it circulates through the body after exposure to the cooled area. This model resulted in predictions differing from the observed drops in temperature at under 5% for both conditions, which stands in stark contrast to the 25% and 36% error the experimenters obtained for their model of the mild and moderate cooling (Table 2).

**Table 2:** Summary of results for experimental cooling of rat spinal column and models of cooling of rat spinal column.

<b>Cooling Temperature (°C)</b>	<b>Experimental Drop (degrees)</b>	<b>Smith Model Drop (degrees)</b>	<b>Our Model Drop (degrees)</b>
22.82	6.67	4.98	6.99
13.66	11.89	7.52	11.95

While this is not the exact model used in the human case, the same approximations were used in its creation: namely those simplifying the geometry of the neck and approximating the effects of blood flow around the area. Thus, the success of this model lends confidence to the human model used in this study.

### *iii. Sensitivity Analysis*

In order to observe the sensitivity of our project to variation in various tissue properties, the different properties were varied and the resulting temperature values after an hour were examined. The parameters changed were density, heat capacity, conductivity, and heat generation terms. These values were varied for the skin, tissue, vertebral bone, and spinal cord (as shown in Table 3 below) and implemented in the model. The original values (“norm”) were reduced by 10% and increased by 10%. These were then recorded as the “min” and “max” values, respectively, as shown in Table 3 below.

**Table 3:** Table of minimum, normal and maximum parameters (density, heat capacity, conductivity and heat generation) of the skin, tissue, bone and spine.

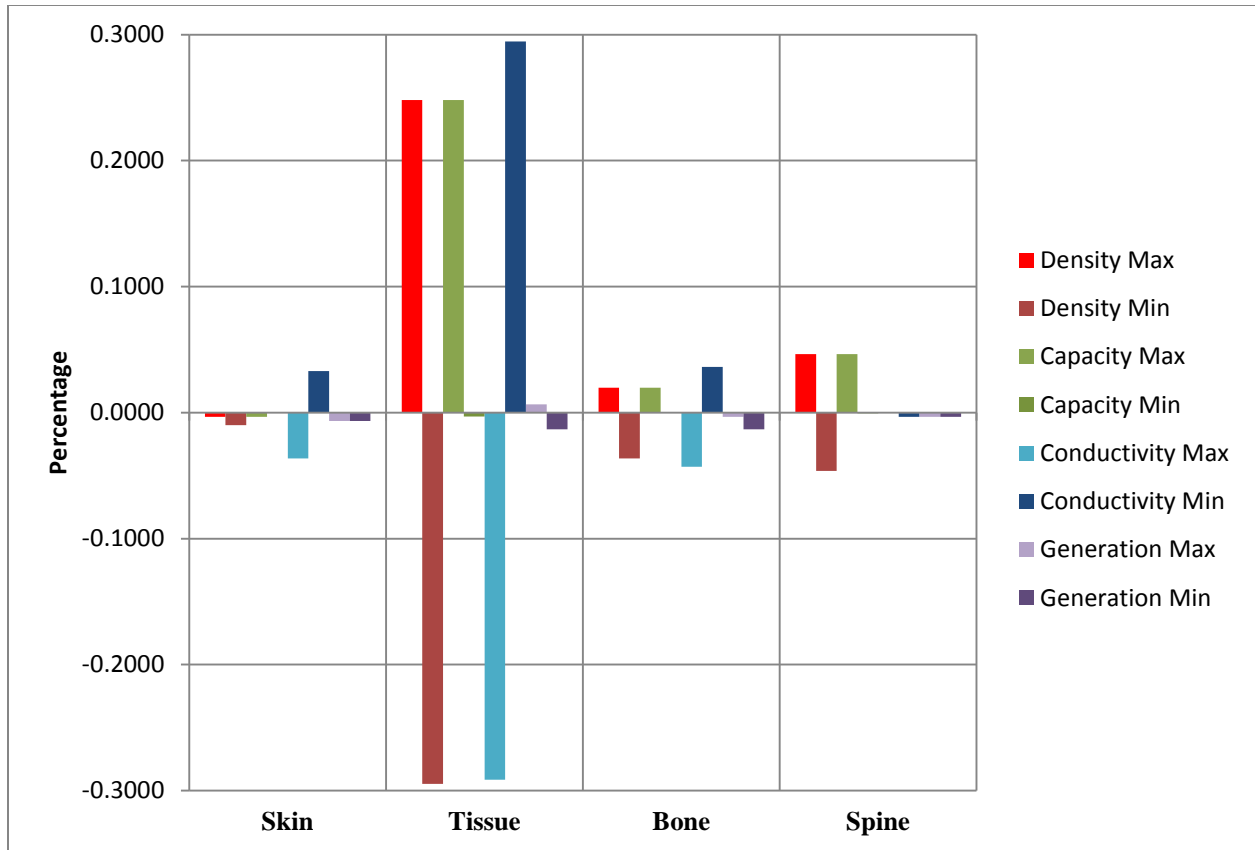
<b>Property</b>	<b>Type</b>	<b>Skin</b>	<b>Tissue</b>	<b>Bone</b>	<b>Spinal</b>
<b>Density (kg/m<sup>3</sup>)</b>	Min	1080	918	1350	918
	Norm	1200	1020	1500	1020
	Max	1320	1122	1650	1122
<b>Heat Capacity (J/kgK)</b>	Min	3240	3202.2	396	3202.2
	Norm	3600	3558	440	3558
	Max	3960	3913.8	484	3913.8
<b>Conductivity (W/mK)</b>	Min	0.477	0.189	0.225	0.189
	Norm	0.53	0.21	0.25	0.21
	Max	0.583	0.231	0.275	0.231
<b>Heat Generation (W/m<sup>3</sup>)</b>	Min	328.5	328.5	328.5	630
	Norm	365	365	365	700
	Max	401.5	401.5	401.5	770

The above variations were used in the model. Each variation was changed while the others were kept constant. The temperature change in the spinal column center (0, -0.0125) was noted for each variation and recorded as shown in Table 4 below.

**Table 4:** Table of spinal temperature changes accompanying changes in parameters shown in Table 3 above.

Property changed	Type of change	Temperature change observed due to changes in the areas below			
		Skin	Tissue	Bone	Spinal
Density (kg/m <sup>3</sup> )	Min	302.18	301.32	302.10	302.07
	Norm	302.21	302.21	302.21	302.21
	Max	302.20	302.96	302.27	302.35
Heat Capacity (J/kgK)	Min	302.18	301.32	302.10	302.07
	Norm	302.21	302.21	302.21	302.21
	Max	302.20	302.96	302.27	302.35
Conductivity (W/mK)	Min	302.31	303.10	302.32	302.20
	Norm	302.21	302.21	302.21	302.21
	Max	302.10	301.33	302.08	302.21
Heat Generation (W/m <sup>3</sup> )	Min	302.19	302.17	302.17	302.20
	Norm	302.21	302.21	302.21	302.21
	Max	302.19	302.23	302.20	302.20

The spinal temperature changes caused by the “min” and “max” variations above were compared to the temperature change caused by corresponding “norm” values and the percent differences calculated and graphed for each variation and property as shown below.



**Figure 11: Variation of Spine Temperature with Changes in Density, Heat Capacity, Conductivity, and Metabolic Heat Generation.** The above graph shows the percent change from the normal value of spine temperature when the minimum and maximum values for each parameter in the skin, tissue, bone, and spine are used.

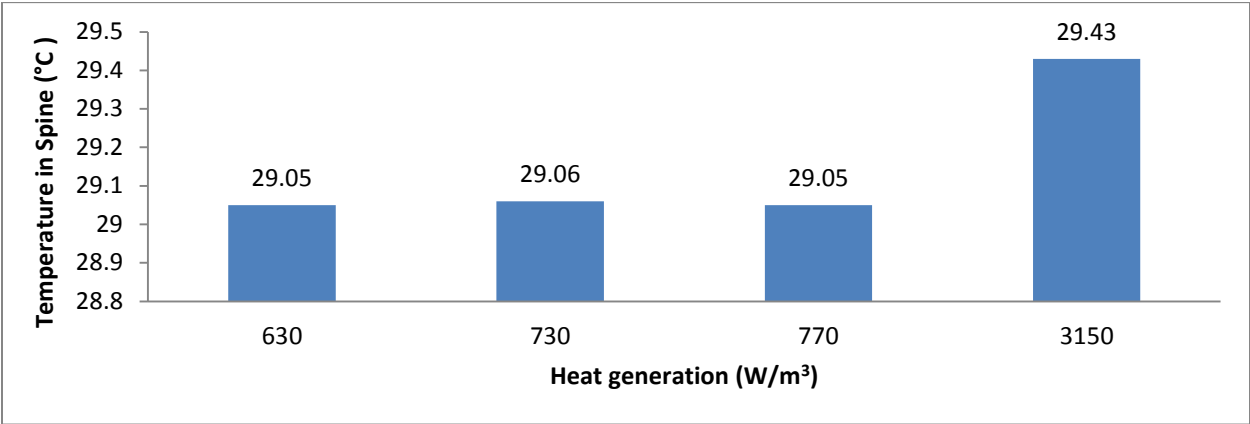
From the figure above, it is evident that the changes in the spinal temperature as a result of variation of densities, conductivity and heat capacity in the layers of the model are very small. Variation of tissue parameters causes the biggest changes in spinal temperature. However, all the above changes are not significant as they are very small. Changes due to variation of heat generation terms in all the layers showed the least amount of difference.

A heat generation term for inflammation was not found. The value used in the project was double the heat generation value of metabolism. In order to show that this value did not affect temperature change due to cooling, a range of heat generation values were used in the model and the corresponding temperature change in the spine was recorded.

**Table 5:** Table of observed temperature changes in the spine as a result of variation heat generation value of the bone.

Heat generation values (W/m <sup>3</sup> )	Observed temperature change in the Spine (°C)
630	29.05
730	29.06
770	29.05
3150	29.43

The values in Table 5 above were plotted in a graph to show how temperature in the spine varied with changing the spinal heat generation term values.



**Figure 12: Spinal Temperature Changes with Changes in Spinal Heat Generation.** The above graph change in spinal temperature when the heat generation of inflammation values are varied.

The difference in temperature values between the lowest value (630 W/m<sup>3</sup>) and the highest value (3150 W/m<sup>3</sup>) was found to be (29.43°C – 29.05°C = 0.38°C) very small. Therefore, increasing heat generation term (up to ~5 times the original estimated value) did not greatly affect the change in temperature in the spine

From the sensitivity analysis carried out above, it was concluded that the model was not sensitive to changes in the parameter values tested (density, conductivity, heat capacity and heat generation) in the skin, tissue, bone and spine layers where these parameters were varied.

## **Conclusions and Design Recommendations**

### *i. Design Recommendations*

Upon examination of the results of the study, several conclusions were drawn. First, the local cooling procedure via the application of a cooling pack alone was capable of decreasing the temperature of the spinal cord to the target temperature of 33°C (306 K). The cooling pad was applied for 30 minutes at 0°C (273 K), then removed for 30 minutes of heating at 37°C (310 K), reapplied for 20 minutes of cooling at 0°C (273 K), and then removed for 30 minutes of heating at 37°C (310 K). The target temperature was reached in less than 45 minutes, and the temperature of the spine stabilized between 31°C – 32°C (304 K – 305 K). In contrast, traditional systemic cooling procedures take an average of four hours to reach a temperature of 33°C. An additional benefit of local cooling is the fact that while the body must still be put in a hypothermic state to ensure the spinal cord reach 33°C, the core temperature can be kept a full two degrees higher (35°C) than it would be using current methods. The core can be kept at nearly normal physiologically temperatures utilizing the fluctuating methodology, which indicates that tissue damage adjacent to the local cooling site due to frostbite can be prevented. Since a major drawback of therapeutic hypothermia use in spinal cord injury treatment is the prevalence of complications arising from the hypothermia, mitigating the severity of this state is a major step forward in treatment. Finally, this protocol does not require systemic cooling, which would prevent the need for the insertion of a cooling catheter. This would decrease the risk of the patient by avoiding invasive and potentially detrimental surgery. By means of cyclic heating and cooling phases of the application area, the spinal cord can remain at temperatures well below 33 °C (306 K) while maintaining the skin temperature well above freezing.

### *ii. Realistic Constraints*

The ideal device to be used for injuries at the cervical spine would need to encircle the neck and be in direct contact with the skin. The pack should be designed so that it is comfortable. Also, the pack should be able to maintain cooling and heating temperatures at constant values to limit the agitation of the patient's injury. This could be accomplished by having two separate inputs of fluid with a certain flow rate kept at the desired temperatures for cooling and heating purposes.

## 5. Appendix A: Mathematical Statement of the Problem

### Governing Equation for Heat Transfer:

Since we are attempting to cool the spinal cord and modeling the process over a circular cross-section, we used the two-dimensional heat transfer equation in cylindrical coordinates with only the transient, conduction, and heat source terms.

$$\rho C_p \frac{\partial T}{\partial t} = k \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 T}{\partial \theta^2} \right) + Q_1 + Q_2$$

$$Q_1 = \text{the heat generation term for base metabolism} = 365 \frac{W}{m^3}$$

$$Q_2 = \text{the heat generation term for inflammation} = 730 \frac{W}{m^3}$$

Since all heat transfer occurs through conduction, the convection term drops out. The tissues are also all creating energy via metabolism in the living subject; this term must be accounted for ( $Q_1$ ). Finally, in the injured tissues, inflammatory processes have been activated by the injury, which results in additional heat generation, which is taken into account by the generation term  $Q_2$ .

In the given protocol, temperature is defined at the skin-cooling pack interface. When the pack is applied, the temperature is constant at 0°C (273 K), and if the pack is removed, the area is heated at a constant temperature of 25°C (298 K). The entire body begins at the normal physiological temperature of 37°C (310 K).



## **6. Appendix B: Solution Strategy**

### *Solver*

The model was solved in the Direct (UMFPACK) linear system solver in COMSOL.

### *Time Step*

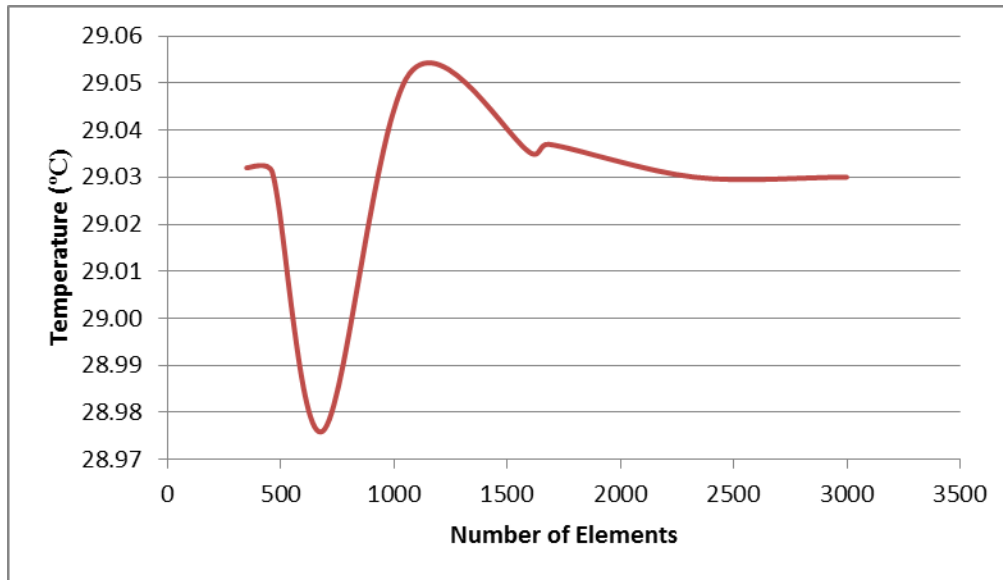
A time step of 0.01 seconds was utilized.

### *Tolerance*

Relative tolerance was 0.1, and absolute tolerance was 0.0010.

### *Mesh Convergence Analysis*

To determine the point at which we effectively eliminated discretization error without wasting valuable time with an overly complex mesh, we ran a mesh convergence analysis. Through this analysis, we determined that while lower element meshes showed significant variation in the spinal cord temperature, after a mesh was created with 2328 elements, results became constant (Figure 6).



**Figure 6: Mesh convergence of modeled schematic.** The above graph shows that as the number of elements increased, the temperature did eventually converge, staying constant at 29.03°C (302.18 K)

The graph above indicates that mesh convergence occurred after 2328 elements, as the constant spinal temperature after this point demonstrates. To avoid error and keep computation time low, we thus used a mesh with 2328 elements.

## 7. Appendix C

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