BEE 453

Temperature Profile Of the Brain During Suspended Animation

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May 5, 2003

1. Executive Summary

In most cases of serious truncal injuries, cardiac arrest occurs within minutes due the severe blood loss. Although many of these injuries are potentially repairable, death is often resulted from fatal brain damage due to insufficient supply of blood. Suspended animation (SA) is a way to preserve the whole organism by lowering brain temperature during prolonged cardiac arrest (often over one hour). A hypothermic flush of cold saline solution is administered through blood vessels to the brain. By lowering the rate of cerebral metabolic activity, damage to the brain is reduced and the brain can be preserved for later cerebral resuscitation. Current studies have focused on animals but no experiment has been implemented on humans yet. In our project, we use GAMBIT and FIDAP to model the temperature profile of the brain during suspended animation. A suitable model of saline flow through blood vessels in the brain is developed to determine how temperature in the outer brain region changes at any given time. From our model, the temperature in the outer brain quickly drops to 8°C after flushing a saline solution of 4°C. While saline is very effective in reducing outer brain temperature, the decrease in brain temperature can be adjusted by using saline solutions of different temperatures.

2. Introduction and Design Objectives

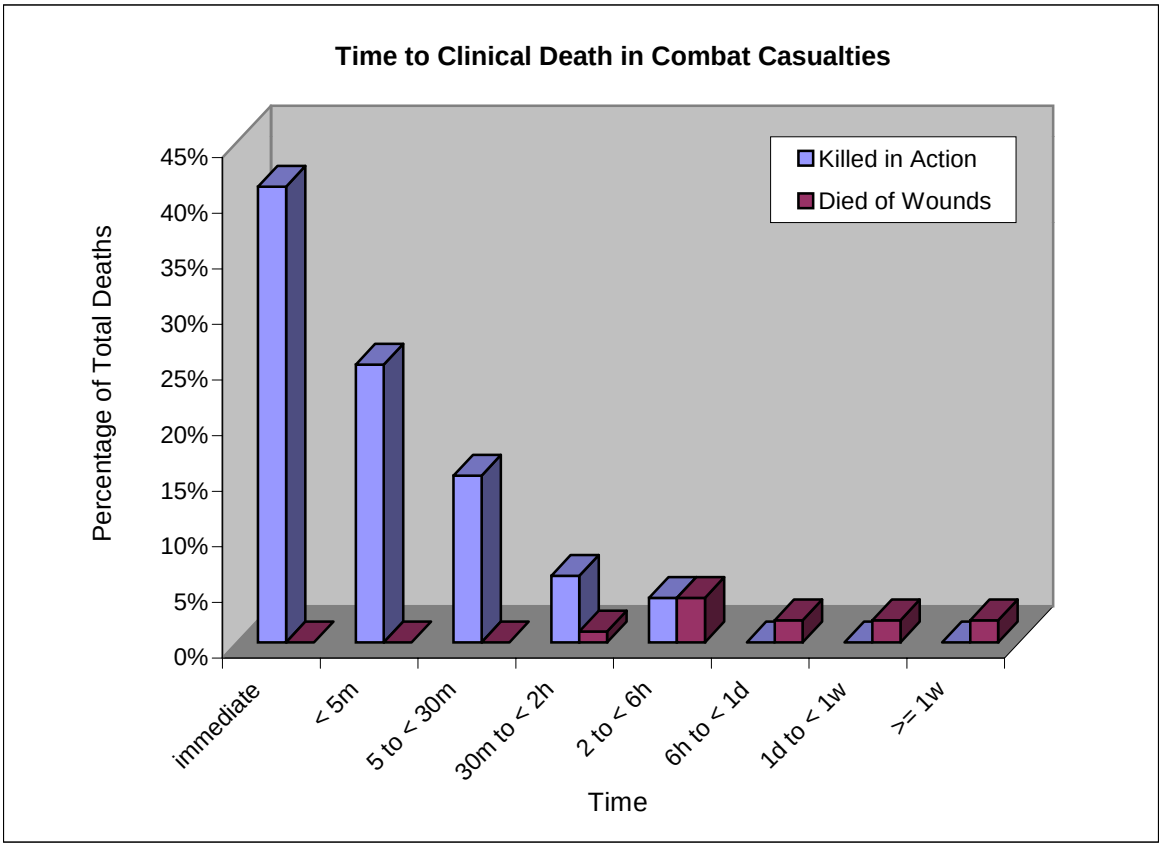


Figure 1. Comparing time to clinical death in combat casualties killed in action and died in wounds [2].

In the majority of casualties killed in military combat and some mortally wounded civilians, cardiac arrest (CA), i.e. no flow of blood, occurs within a few minutes of truncal injury as a result of internal exsanguination (i.e. internal bleeding). These victims are given up as "unresuscitable", although many, in the absence of brain trauma, die from potentially repairable injuries. Suspended animation (SA) is a way to preserve the brain when there is no blood flow in the brain. It buys time for repair and transport in the brain during pulselessness. SA reduces damage to the brain, which is critical for the achievement of later cerebral resuscitation, and allows for survival without brain damage. During SA, a hypothermic flush of isotonic saline solution is administered into the femoral artery through the aortic arch. This procedure is carried out at the start of prolonged exsanguination following cardiac arrest. Through blood vessels, the cold saline solution reaches the brain to lower its temperature and reduce the rate of cerebral metabolic activity.

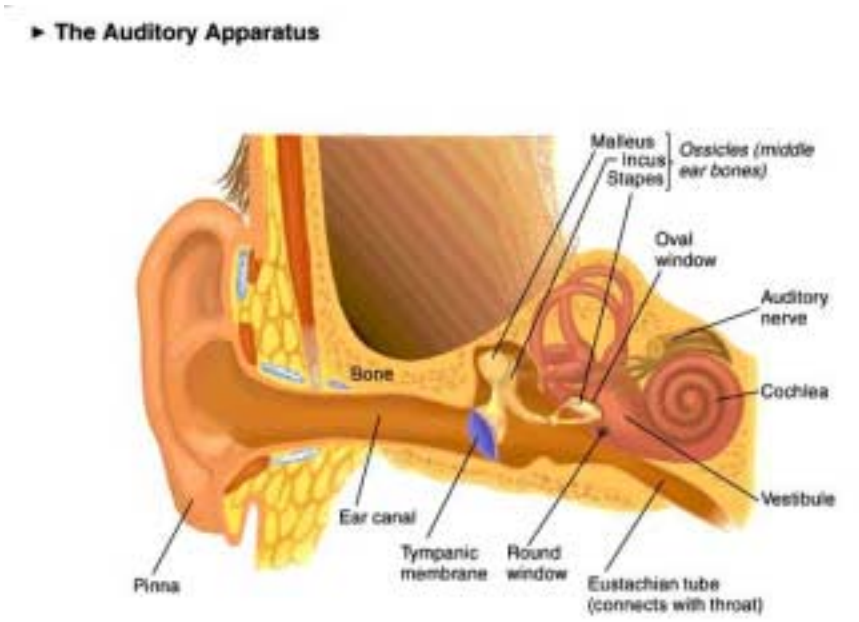


Figure 2. Structures of the ear [http://www.driesen.com/auditoryapparatus1.jpg].

There is ongoing research to model temperature changes at the tympanic membrane in the middle ear during suspended animation. However, these experiments have only been performed on animals, particularly dogs. Suspended animation has not been used on humans yet.

With reference to previous studies, a normal saline solution (NSS) of 500 ml at 4°C enhances survival functional recovery without any neurologic deficit or histologic brain damage. In our study, we use an axisymmetric model of the brain to monitor its temperature changes when a saline solution of 4°C is applied across the brain. Using GAMBIT and FIDAP, we construct the temperature profile of the entire brain during the saline flush.

The bioheat equation is used to solve the associated heat transfer problem in our model. Since the bioheat equation is best applied in regions where blood flow is dominated by capillary transportation, we focus our model on the outer brain where capillaries are most concentrated. We use an axisymmetric design of the brain. Due to symmetrical consideration, only a lateral section of the brain is examined. A schematic of our model is shown in below:

The brain, together with surrounding tissues, is represented by a hemisphere.

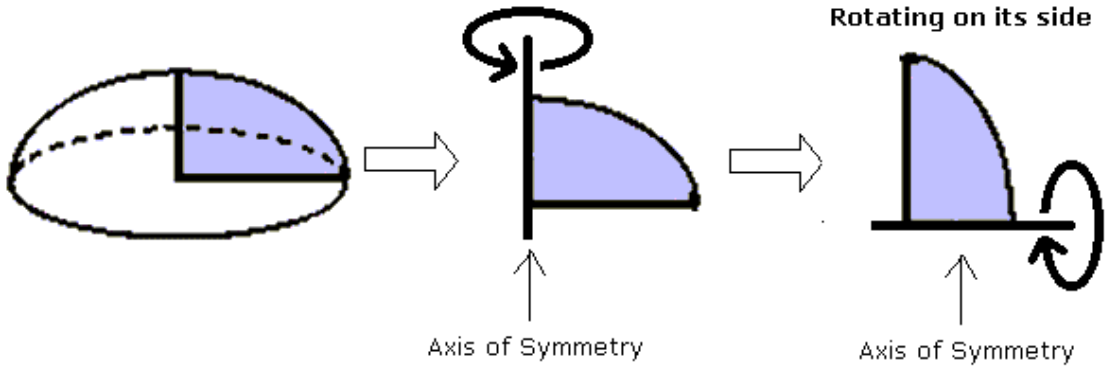


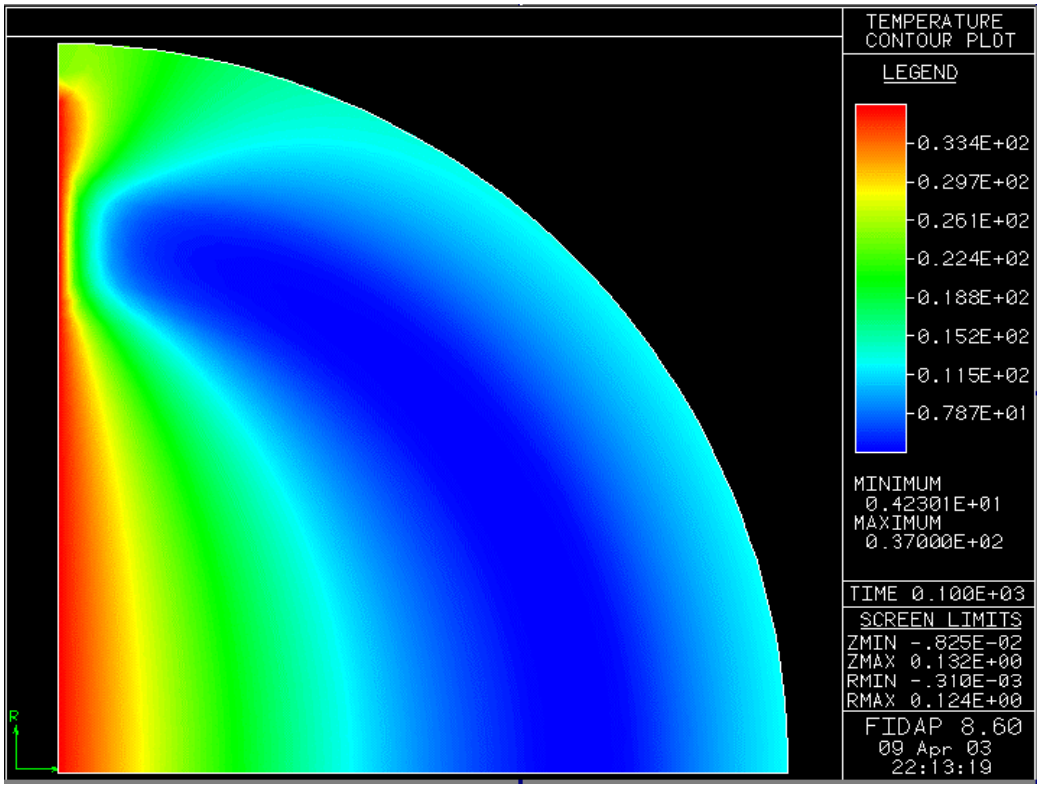
Figure 3. Axi-symmetric model of the brain

Hence, a quarter-circle is used in our simulation model.

Since the rate of cerebral metabolic activity is substantially reduced by the low temperature of the saline solution, it is assumed that there is no heat generation in the brain during the process. It is also assumed that all thermal properties are constant and isotropic.

3. Results and Discussion

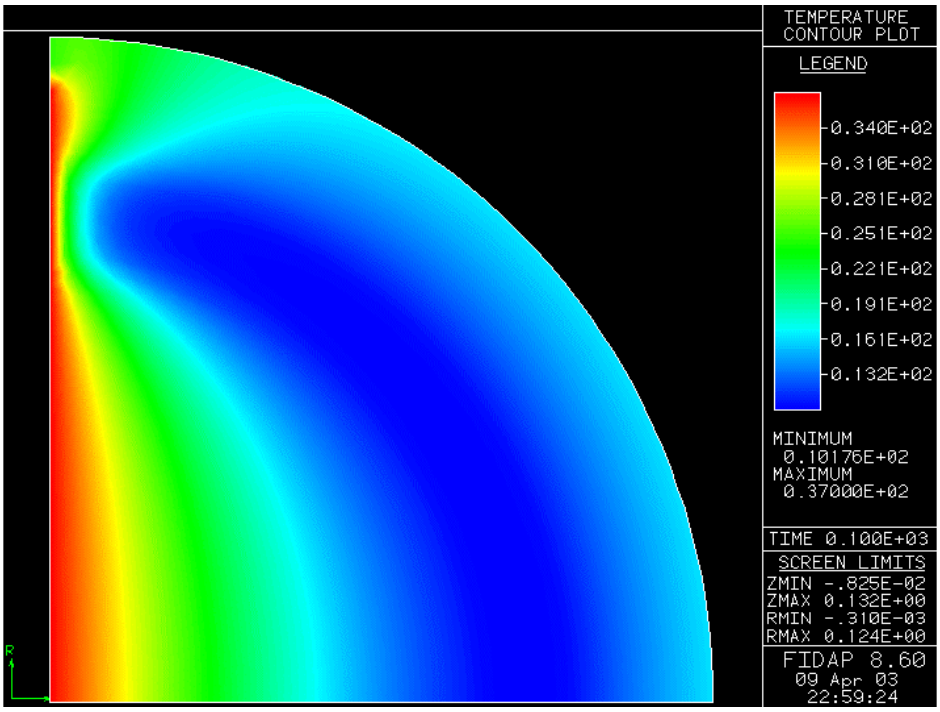
Temperature contour when the cold saline is passing into the brain:



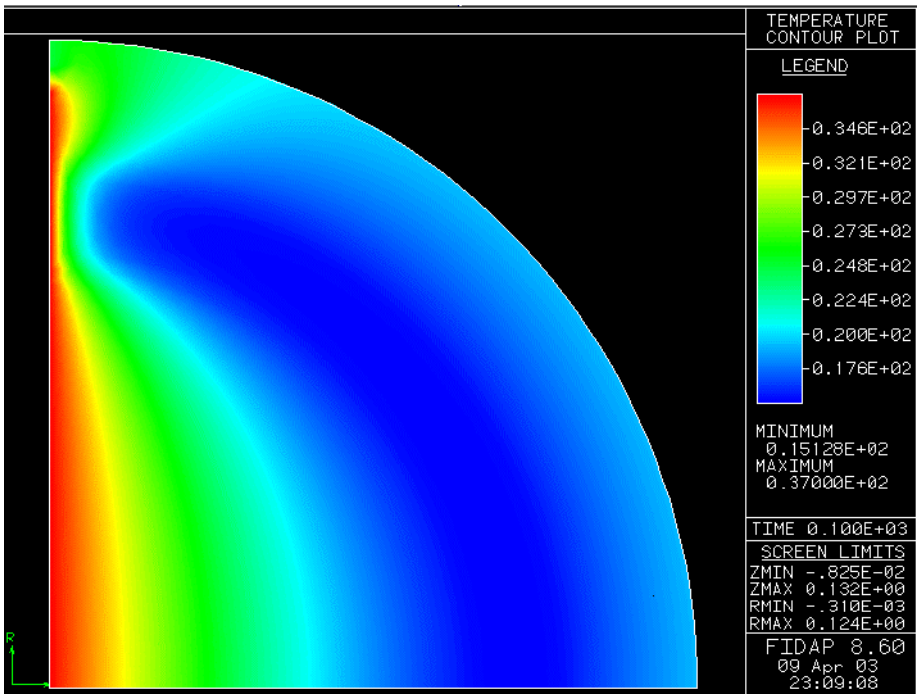
With reference to previous study, we expected the temperature of the brain to be lowered to 5-10^{o}C with the 4^{o}C saline. From the contour plot, it can be shown that the temperature of the outer brain has dropped to a temperature of around 8^{o}C. The injection has effectively cooled down the region of the brain. However, the inner region of the brain was not cooled as much and it stayed at a higher temperature. This happened because we assumed that interaction between the cold saline and the tissues occurred only in the outer brain region. The inner region was not cooled directly by the saline but purely by diffusion.

Sensitivity Analysis

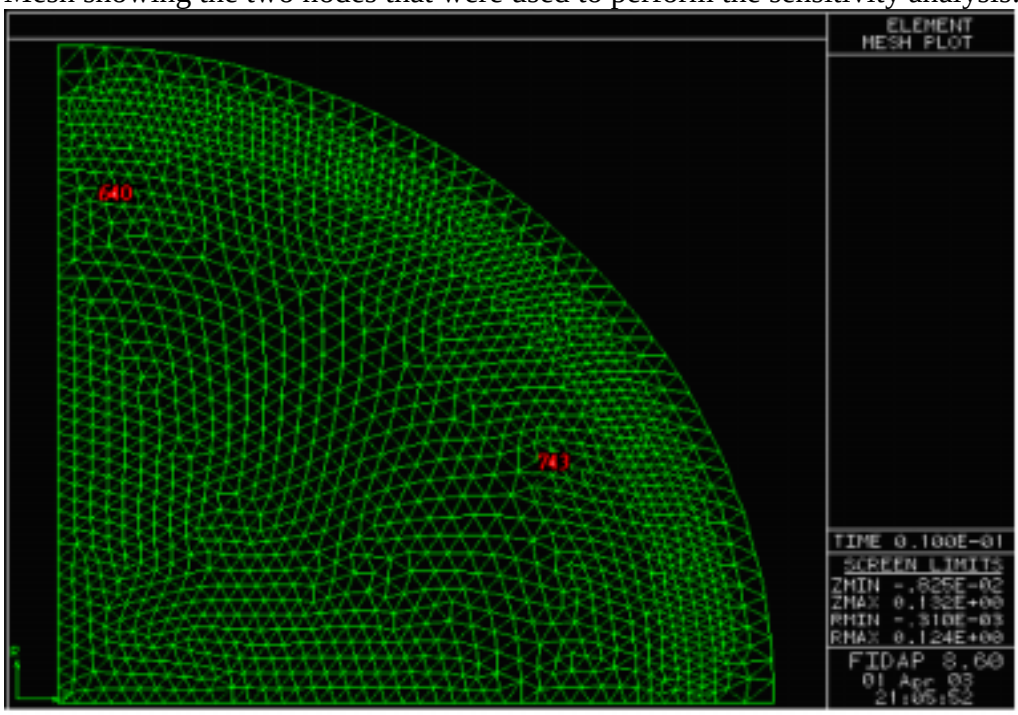
When the temperature of the saline is increased to 10°C, the following temperature contour is obtained (temperature of outer brain = 13°C):



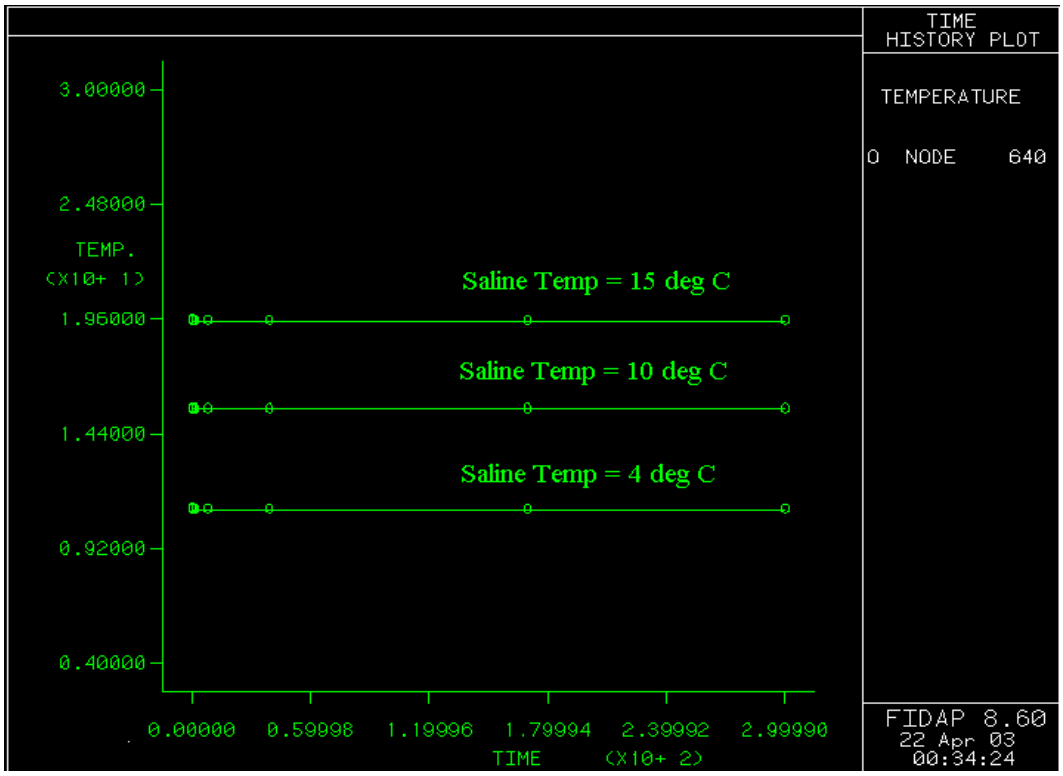
When the temperature of the saline is further increased to 15°C, the following temperature contour is obtained (temperature of outer brain = 18°C):



Mesh showing the two nodes that were used to perform the sensitivity analysis:

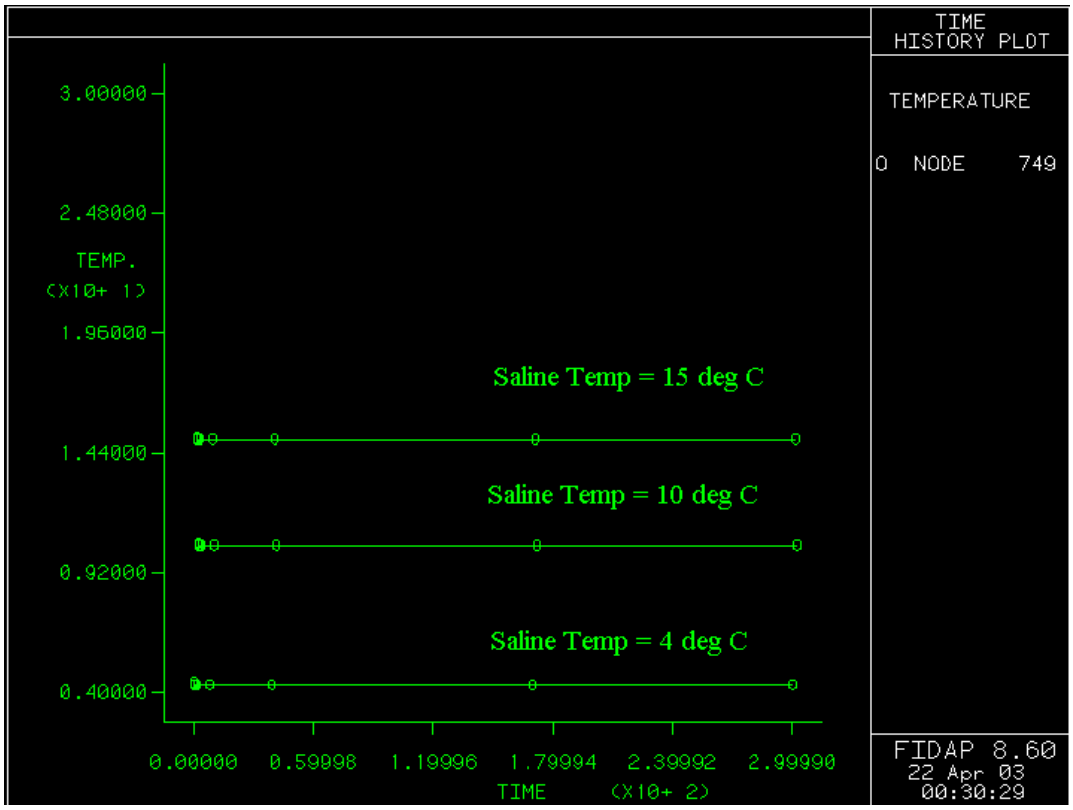


The following plot shows the effect of the saline temperature (node 640 is in the interior of inner brain region):



Saline Temperature (^{o}C)	Temperature (^{o}C)	% change
4	**11.3**	**0**
10	**15.4**	**36**
15	**19.6**	**74**

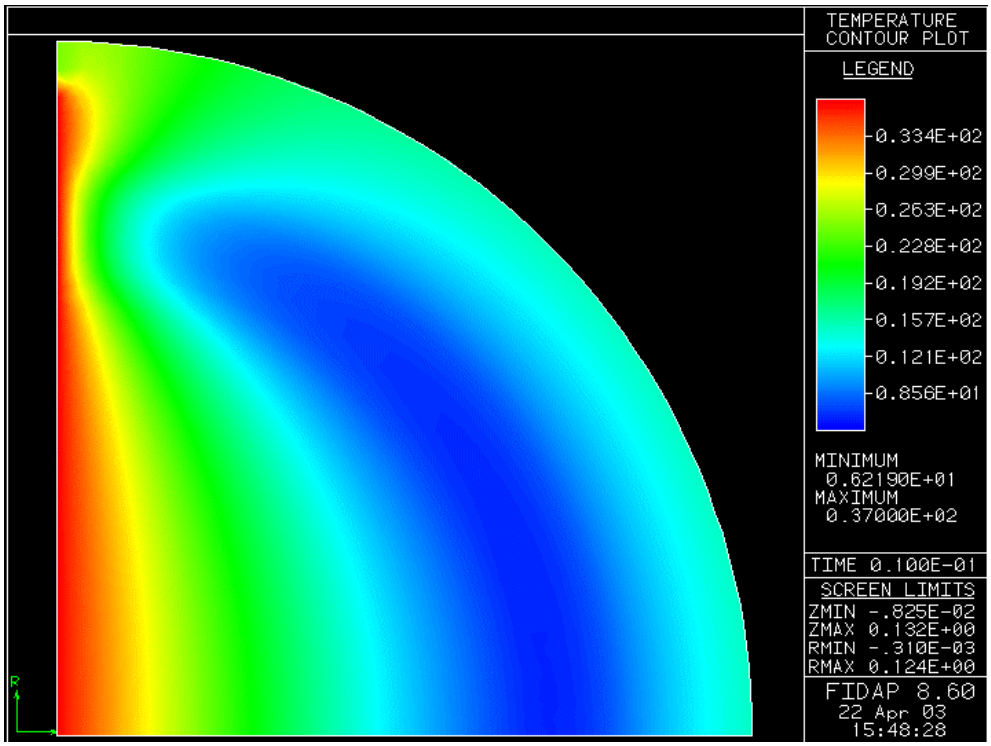
The following plot shows the effect of the saline temperature (node 749 is in the interior of inner brain region):



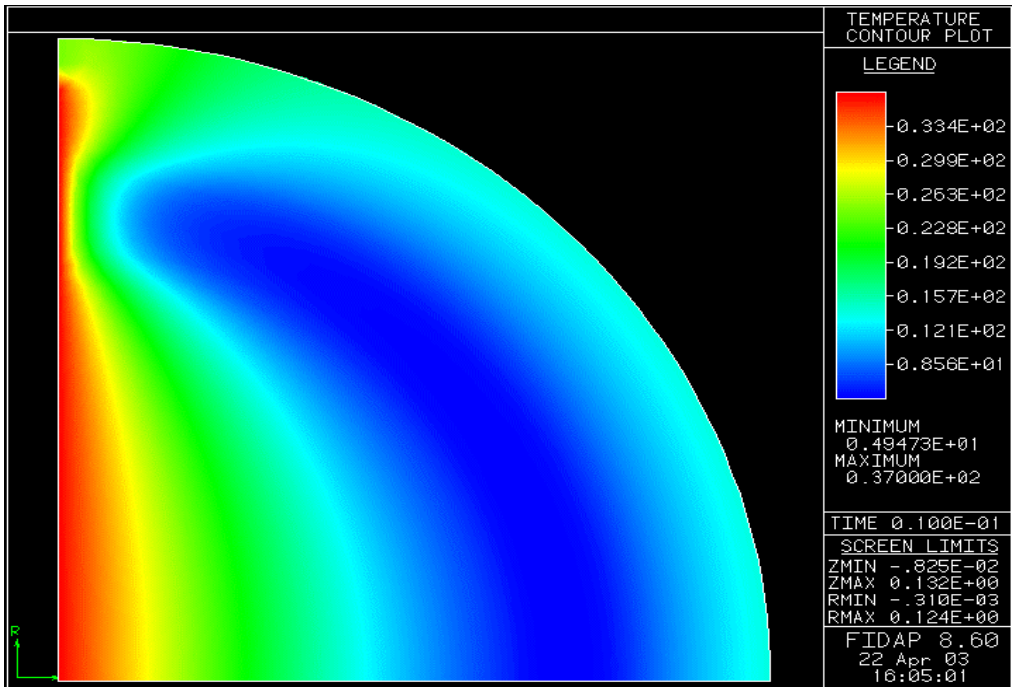
Saline Temperature (°C)	Temperature (°C)	% change
4	**4.1**	**0**
10	**10.2**	**149**
15	**15**	**266**

From these, we can conclude that the interior region is more sensitive to a change in saline temperature. A 6 °C increase in saline temperature would cause a 149% increase in the temperature at node 749 but only a 36% increase at node 640. The temperature at the region close to the boundary is largely controlled by the boundary condition and is less sensitive to changes in saline temperature.

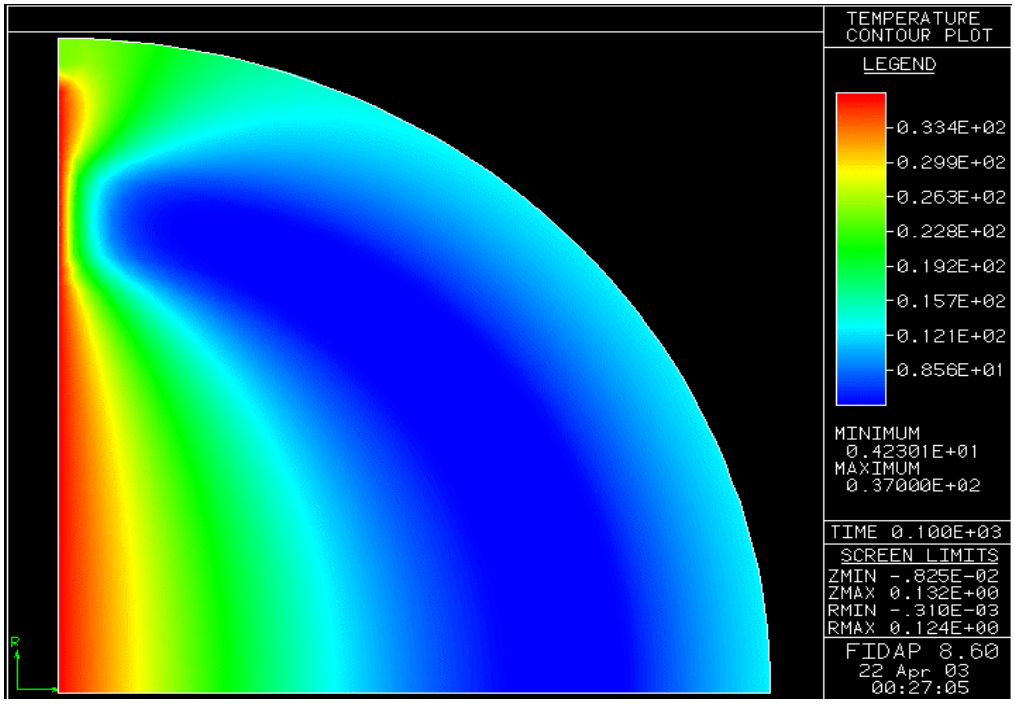
When the flow rate of the saline (4°C) is halved, the following temperature contour is obtained:



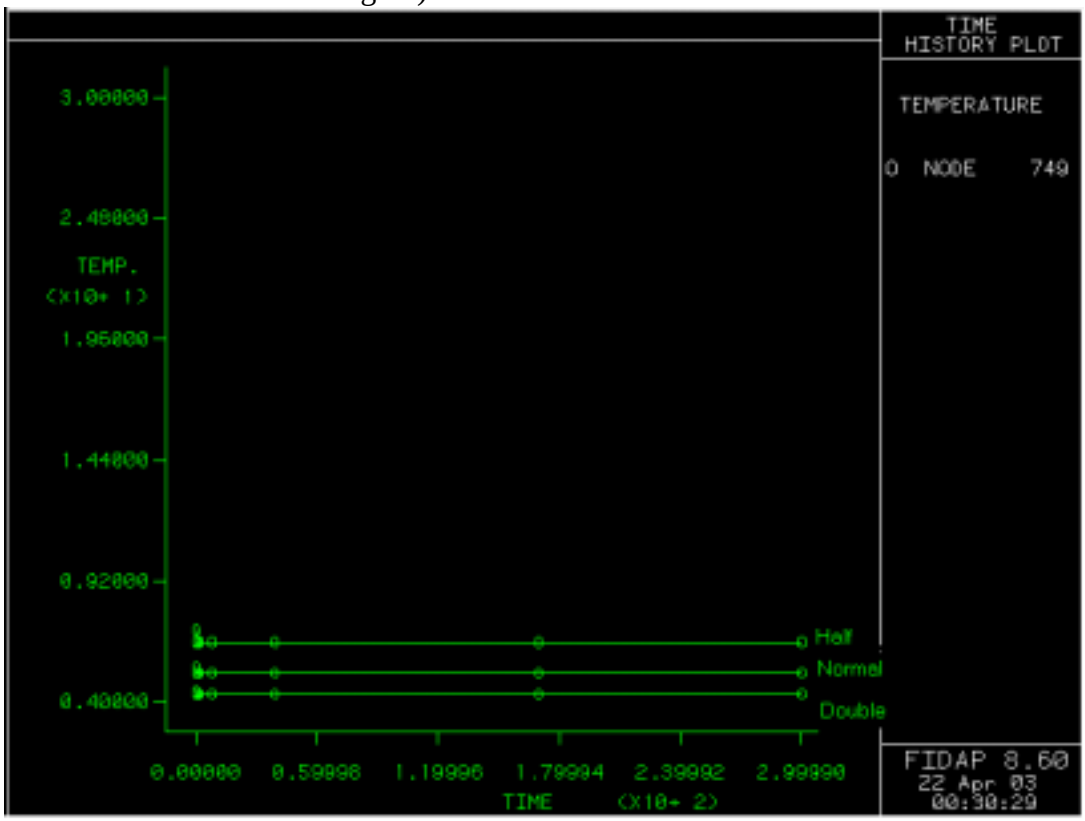
At the normal flow rate of the saline (4°C), the following temperature contour is obtained:



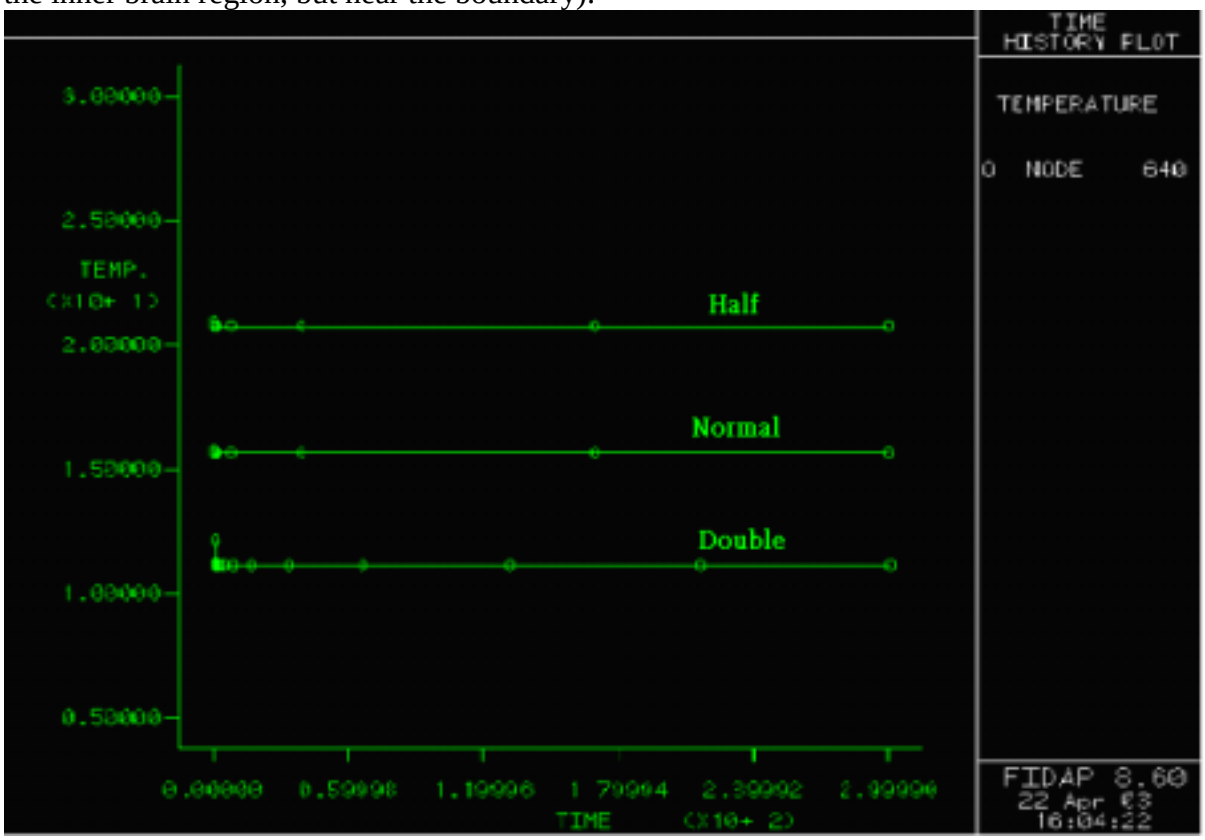
When the flow rate of the saline (4°C) is doubled, the following temperature contour is obtained:



The following plot shows the effect of different flow rates on temperature (node 749 is in the interior of inner brain region):



The following plot shows the effect of different flow rates on temperature (node 640 is in the inner brain region, but near the boundary):



Condition of flow	Temperature (°C)	% change
Half	**20.05**	**33**
Normal	**15.05**	**0**
Double	**11**	**-27**

4. Conclusions and Design Recommendations

Our model shows how temperature is changing in the outer brain region during the saline flush in suspended animation (SA). Saline solution is very effective in cooling the brain for suspended animation. Injection of saline at 4°C causes the outer region of the brain to drop to 8°C almost instantly. The fast cooling action of saline is very important in reducing cerebral metabolic activity and hence later damage to the brain in resuscitation. The final reduced temperature of the outer brain can be adjusted by varying saline temperature to meet different requirements for SA performed on different people or animals.

In our study, we have only shown that saline injection is a very effective and critical procedure in SA. Further studies can focus on determining the optimal time and temperature of the injection for the best results in reducing brain damage. We have to find out the lowest possible temperature the brain can reach before determining the optimal conditions of the saline injection. If temperature of the brain is lowered to too great an extent, ice crystals will form in brain cells and irreparable brain damage can occur. It is also useful to find out if more than one injection is needed for optimal results and the required time between each injection.

By using a computer-aided analysis of saline injection, we can determine the effectiveness of brain cooling in suspended animation. On the one hand, we can obtain quantitative and objective data on the temperature profile of the brain during SA, and hence gain invaluable information and insight on how to further improve SA. On the other hand, we can save a lot of time and effort by performing the analysis by computer simulations instead of on real humans. While we can get reliable data and conclusions, we can avoid the huge costs of experimentation spent on experimental equipments and chemicals, as well as the time for sampling, controlling and experimental procedures. Using computer simulations, we can have the benefit of getting reliably accurate useful results without expending to much cost. In addition, we cannot possibly perform experiments of SA on humans due to ethical concerns, and the computer-aided design provides a useful tool for a simulated experiment on the human brain.

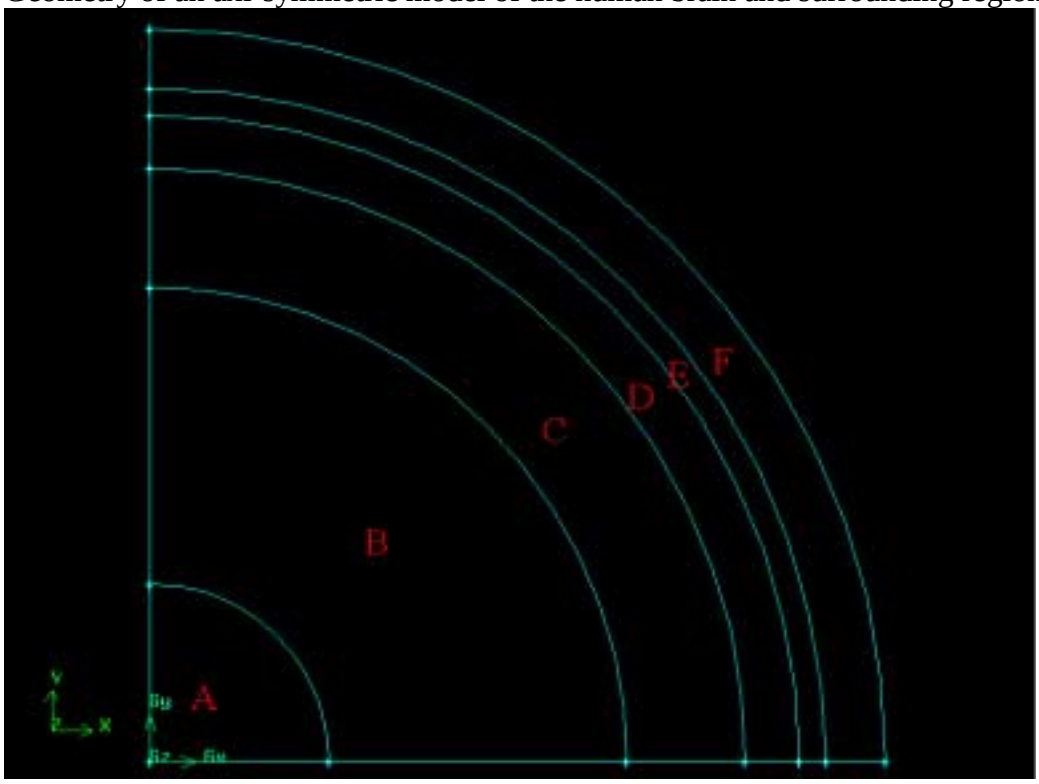
Other improvements can be made to our model. Our model is a simplified version of the brain. Since the brain is not really symmetrical, we can account for the asymmetry and irregularity of the brain by employing a 3D instead of a 2D analysis. To further increase the accuracy of our results, we can determine the actual convection coefficient of the saline solution instead of using a rough estimate. In addition, we can obtain more specific geometrical and material property data for the brain. It is desirable to focus our study on lowering temperature in specific regions in the brain so that materials necessary for the metabolism of the brain are not destroyed in the cooling process. Since the appropriate saline temperature varies for different brain dimensions, it is useful to simulate the model for various brain sizes.

5. Appendices

Appendix A: Geometry and Mathematical Statement of Problem

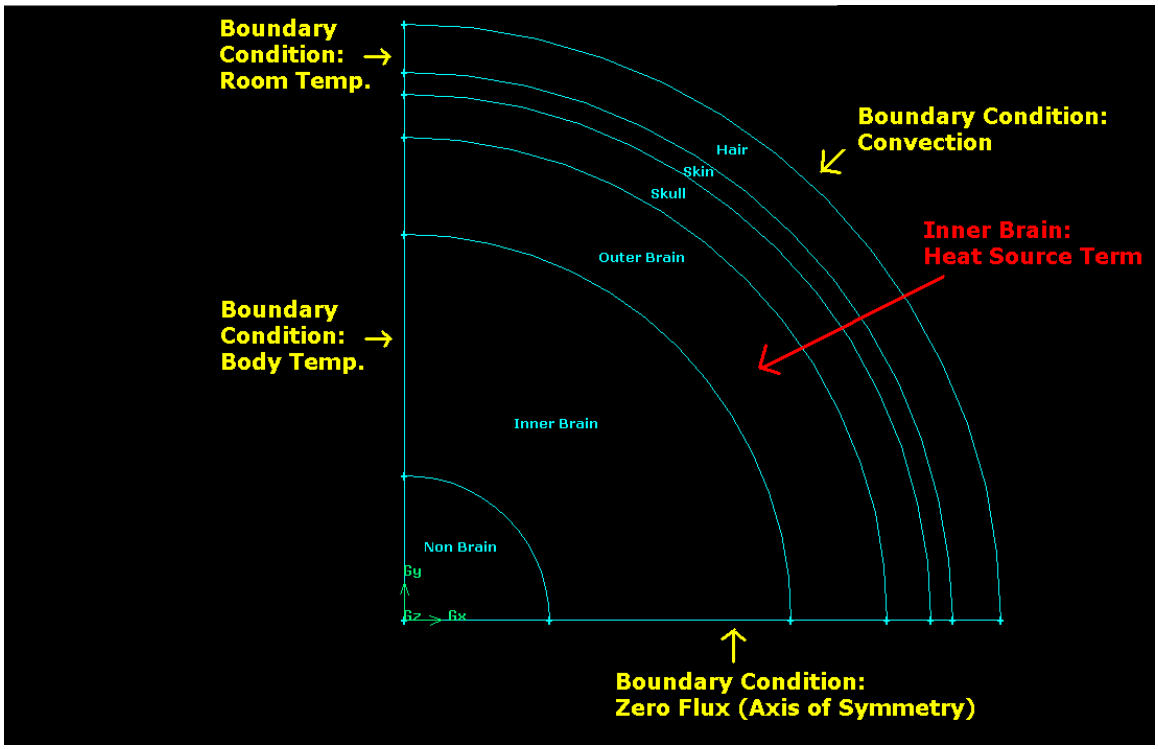
Geometry

Geometry of an axi-symmetric model of the human brain and surrounding regions:



A: Non-brain tissue	Thickness = 30mm
B: Inner brain	Thickness = 50mm
C: Outer brain	Thickness = 20mm
D: Skull	Thickness = 9mm
E: Skin	Thickness = 4.5mm
F: Hair	Thickness = 10mm

Diagram showing Boundary Conditions and Initial Conditions on the geometry of the brain:



Governing Equations

Since the entire human brain is filled with blood capillaries, the bioheat equation is used to solve the heat transfer problem.

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \rho_b c_b \dot{V}_b (T_a - T) + Q$$

where $\dot{V}_b$ is the flow rate of saline, c are thermal properties of the tissue, ρ_b and c_b are thermal properties of saline.

Heat generation term Q can be ignored since metabolic activities in the brain are suspended.

Boundary Conditions

(1) Temperature at tissue (nonbrain, inner and outer brain, skull and skin) far away from the brain is not cooled and is maintained at body temperature.
(2) Temperature of the hair region in maintained at room temperature.
(3) Heat flux is zero at the axis of symmetry.

(4) Convection occurs at the outer surface if the head where ambient air flows over the surface:

$$-k\frac{\partial T}{\partial r}\bigg|_{r=r_{head}} = h(T\big|_{r=r_{head}} - T_\infty)$$

A convective coefficient of 20 W/m^2 K is used.

Initial Conditions

Before cold saline flows into the brain, the temperature of the brain is 37^{o}C:

$T(t=0)$ = 37^{o}C

Properties

Flow rate of saline	$\dot{V}_b = (750ml/\min)/(1018.9cm^3) = 0.01227/s$
Arterial saline temperature	$T_a = 4^oC$
Properties of brain tissue	k_{brain} = 0.16-0.57 W/m K
	$\rho_{brain} = 1040\ kg/m^3$
	c_{brain} = 3664 J/kg K
Properties of saline	ρ_b = 998 kg/m3
	c_b = 4183 J/kg K
Properties of skull	k_{skull} = 0.75 W/m K
	$\rho_{skull} = 1810\ kg/m^3$
	c_{skull} = 1220 J/kg K
Properties of skin	k_{skin} = 1.5 W/m K
	$\rho_{skin} = 1020\ kg/m^3$
	c_{skull} = 3662 J/kg K
Properties of hair	k_{hair} = 0.18 W/m K
	$\rho_{hair} = 265\ kg/m^3$
	c_{hair} = 1100 J/kg K

For sources, see reference [4].

Appendix B: Solution Details of FIDAP Implementation

FIDAP Implementation

Problem Statement

Geometry	AXISYMMETRY
Flow regime	INCOMPRESSIBLE
Simulation type	TRANSIENT
Flow type	LAMINAR
Convective term	LINEAR
Fluid type	NEWTONIAN
Momentum Equation	NOMOMENTUM
Temperature dependence	ENERGY
Surface type	FIXED
Structural solver	NOSTRUCTURAL
Elasticity	NOREMESHING
Number of phases	SINGLEPHASE

To include the heat sink term from the cold saline, a LINEAR heat source term is used in FIDAP.

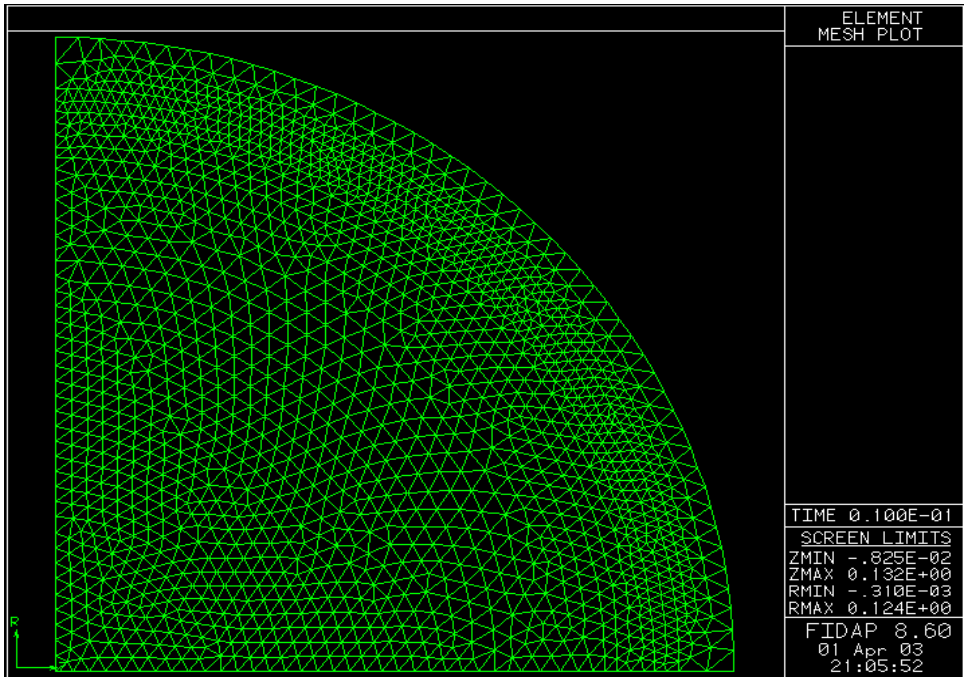
Solution Statement

Solution Method	Successive Substitution (S.S) =10
Solution tolerance	Default value was used
Residual tolerance	Default value was used
Relaxation factor	ACCF = 0

Time Integration Statement

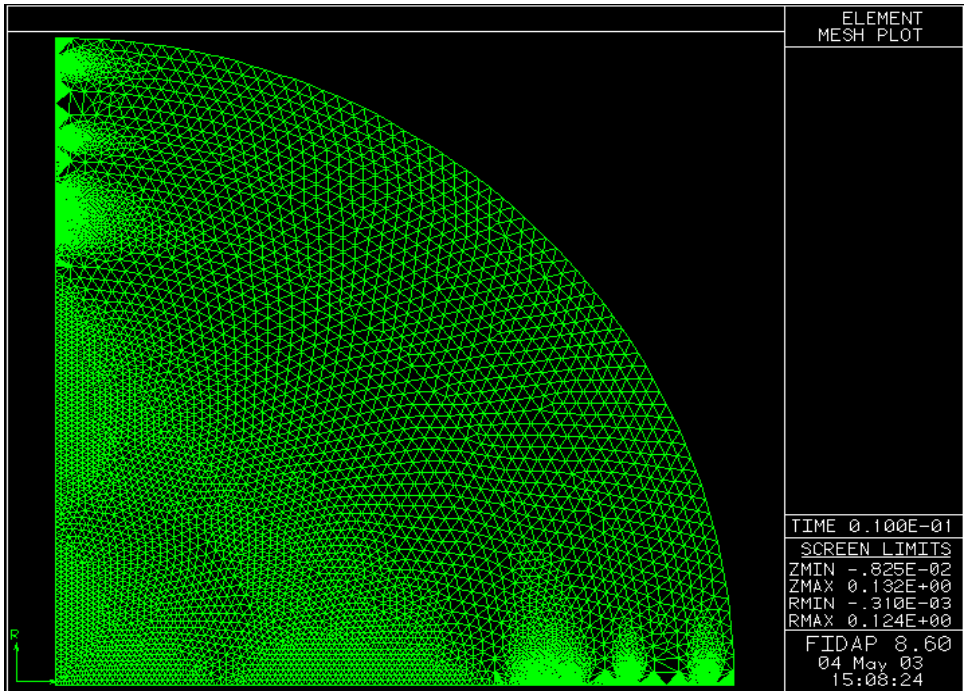
Time Integration	BACKWARD
No. Time Steps	NSTEP = 500
Starting time	TSTART = 0
Ending time	TEND = 300
Time Increment	DT = 0.01
Time Stepping Algorithm	VARIABLE = 0.01
No. fixed steps	NOFIXED = 5
Max increase factor	INCMAX = 10

Mesh Plot



No. of elements: 3208

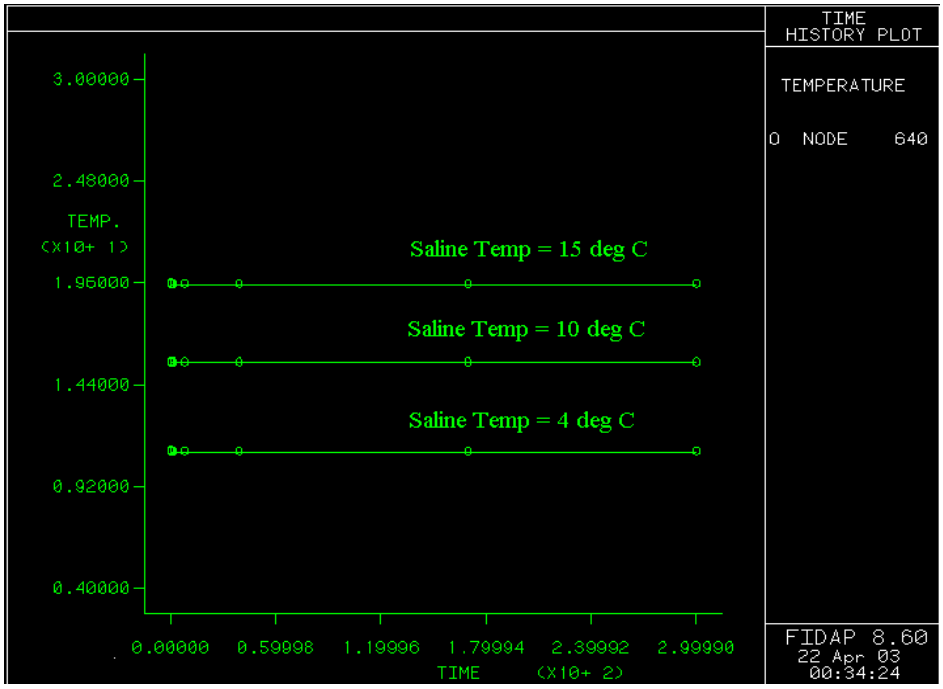
Mesh Refinement



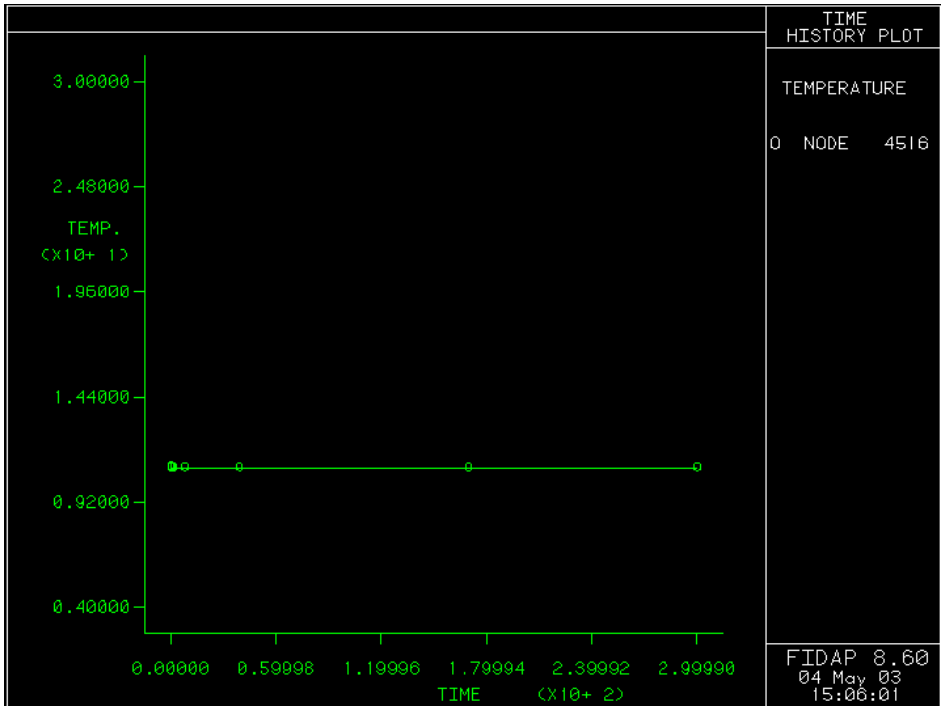
No. of elements: 14352

Convergence of the Solution

Original mesh:

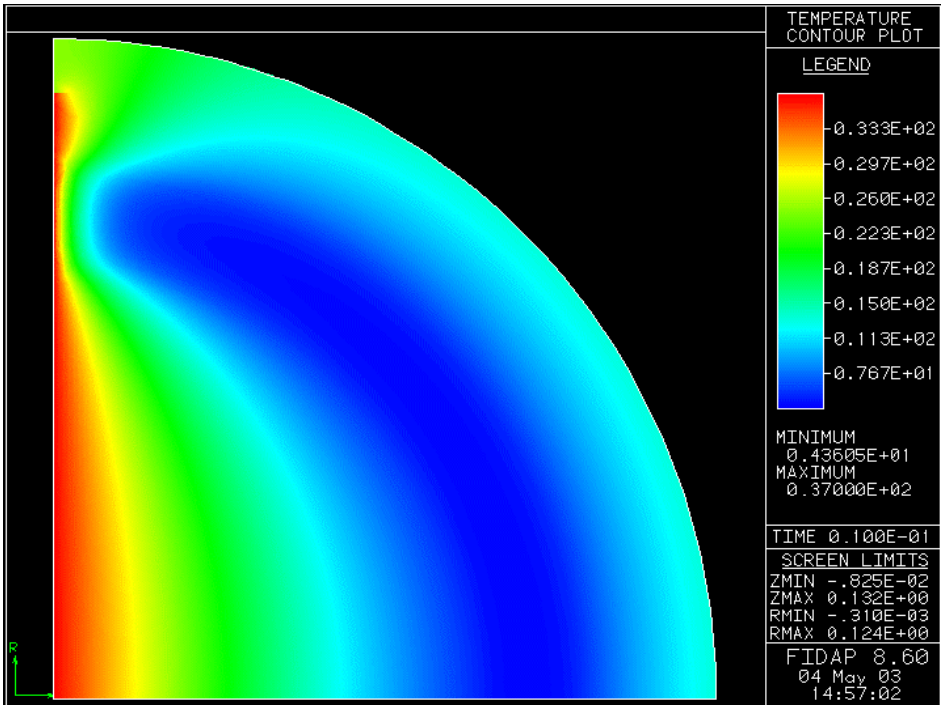


Refined Mesh (Saline temperature = 4^{o}C):



Both of these history plots are taken from similar positions from the two mesh plots. We can see that the temperature at these 2 points reaches the same value and hence we can conclude that the solution has converged and our solution does not depend on the mesh used. The contour plot below shows that the temperature profile of the entire region does not change with the mesh and confirms that the solution has converged.

Contour plot from refined mesh:



References

[1] Bellamy R.F., The causes of death in conventional land warfare: implications for combat casualty care research. *Milit. Med.* 149 (1984), pp. 55–62.

[2] Bellamy R., Safar P., Tisherman S.A., Basford R., Bruttig S.P., Capone A., Dubick M.A., Ernster L., Hattler B.G., Hochachka Jr, P., Klain M., Kochanek P.M., Kofke W.A., Lancaster J.R., McGowan F.X., Oeltgen P.R., Severinghaus J.W., Taylor M.J. and Zar H., Suspended animation for delayed resuscitation. *Crit. Care Med.* 24/S (1996), pp. S24–S47.

[3] Woods R. J., Prueckner S., Safar P., Takasu A., Tisherman S. A., Jackson E.K., Radovsky A., Kochanek P., Behringer W., Stezoski S.W. and Adenosine R.H.˙ by aortic flush fails to augment the brain preservation effect of mild hypothermia during exsanguination cardiac arrest in dogs — an exploratory study. *Resuscitation* Volume 44, Issue 1, March 2000, Pages 47-59.

[4] Dy E., Ross R. , Tataria J., Lundeen A., Connelly J.. Bald is Beautiful, but is it Warm? *A look into the danger of hypothermia on the walk to Riley Robb. BEE 453 2001 Project.*