Heat Loss in the Carotid Artery During Selective Brain Cooling in Humans

Final Project Report
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BEE 453 Computer-Aided Engineering: Applications to Biomedical Processes
Professor Ashim Datta

Suneth Attygalle
Hussein Girnary
Natalie Jeffrey
Sean Lee
Rosa Torre

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Executive Summary

Heat flow in the neck was simulated in FLUENT to study countercurrent effects of cooling blood in the carotid artery during selective brain cooling. The simulation was performed in order to verify Zhu's theory (used as a basis for our methodology) and to determine the contribution of countercurrent exchange by comparing results to a heat flow model without exchange. The surface temperature of the neck and flow rates within the vessels were varied to determine the specific effects of countercurrent exchange. With ambient skin temperature (25°C) and normal blood flow rate (120 ml/min); our model demonstrates that the average temperature of the arterial blood reaching the brain drops by 1.18°C while traveling through the neck. The effect of the countercurrent exchange alone contributes 0.88°C to this temperature decay. Placing an ice pack on the neck surface can further decrease the arterial blood temperature by as much as 1.0°C. This indicates that placing an ice pack on the neck does aid in selective brain cooling and that countercurrent exchange has a significant impact in cooling as well. The overall temperature drop of blood between the inlet to the carotid artery and the outlet was found to decrease with increasing blood flow rates and surface temperatures, verifying the trends modeled in Zhu's analysis. Zhu's theoretical study, however showed a temperature drop of 0.35°C at a blood flow rate of 240 ml/min with vein inlet blood temperature at 29°C and neck temperature at 19°C whereas ours showed a temperature drop above 0.85°C. Sensitivity analysis was performed to test the stability of our solution and to discover factors that might affect arterial outlet temperature. The factors that had the most influence on penetration depth were the specific heat of the blood and varying the thermal conductivity of the tissue. This project could be expanded upon by considering more variations in geometry, such as center-to center spacing, vessel eccentricity and modeling multiple vessels. This would allow for a better model of the true behavior of heat flow in the neck.

INTRODUCTION

Countercurrent heat transfer within the circulatory system of many aquatic animals is a common method of limiting heat loss to the surrounding cold water. As cold blood from the extremities passes warm blood from the body, the opposing parallel flows maintain a constant exchange gradient along their length, thus reducing heat loss and maintaining a near constant temperature within the extremity. It has been suggested that, within the human neck, countercurrent exchange between the main carotid artery and the vein in parallel may be a method of selective brain cooling during hyperthermia. This project seeks to simulate and study the cooling of blood in the carotid artery on the way to the brain using FLUENT.

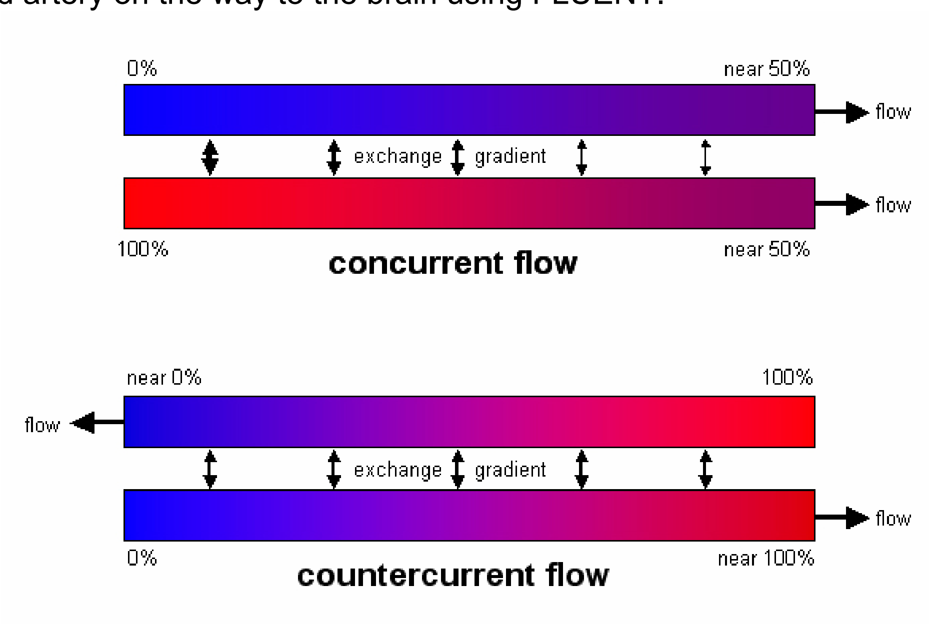

Figure 1: Concurrent and countercurrent exchange (http://en.wikipedia.org)

Based from the theoretical work done by Zhu, this project takes into account heat loss to the countercurrent vein as well as heat loss to the surrounding tissue, whereas prior theoretical works ignored heat loss to the surrounding tissue. Thus, the results from our project will likely be closest to reality than previous studies. Specifically, we will simulate different temperature boundary conditions on the surface of the neck such as placing an icepack on the neck (temperature = 0) or constant room temperature. The relative contributions of heat conduction and countercurrent exchange will be considered under these different boundary conditions. The primary variable being considered is the outlet temperature of the artery, which will be the temperature of blood going to the brain.

DESIGN OBJECTIVES:

Specific design objectives are as follows:

- Observe selective brain cooling by simulating heat flow in the neck, accounting for heat conduction and countercurrent exchange
- Verify Zhu's theoretical analysis using numerical methods
- Determine if cooling neck surface affects arterial outlet temperature
- Determine effects of different blood flow rates on arterial outlet temperature
- Determine contribution of countercurrent exchange by comparing results with heat flow without countercurrent exchange

SCHEMATIC:

The neck and both blood vessels were simplified to perfect cylinders. The material properties that were used were taken from Zhu's paper to compare the results from his theoretical analysis.

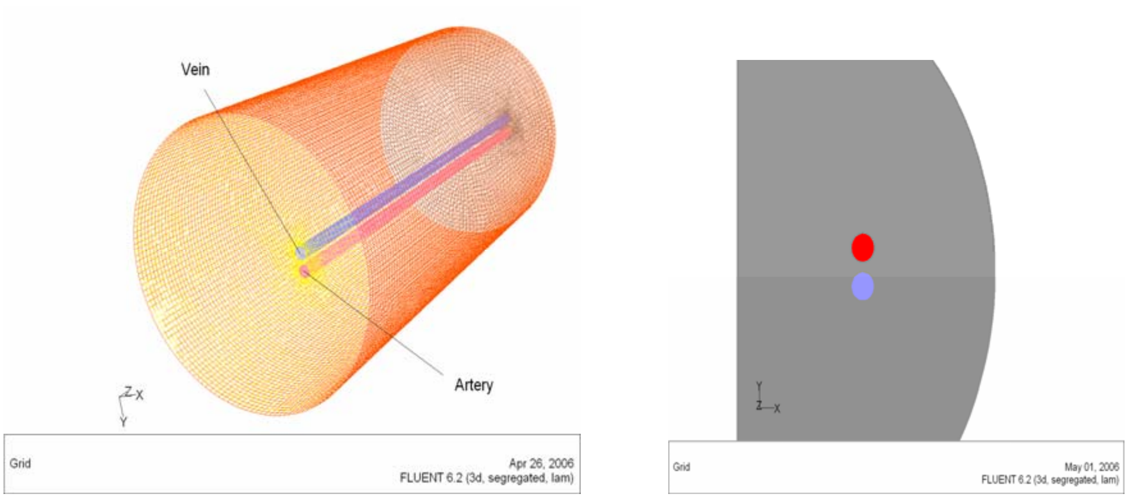

Figure 2: a. 3D schematic of neck b. Cross section of a.

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The report details the heat loss in the neck and its role in selective brain cooling as well as our results from the simulations. We then evaluate the contribution of heat conduction and countercurrent exchange in arterial temperature drop and determine if cooling the neck surface aids in selective brain cooling. We present a sensitivity analysis of material properties and flow conditions and provide design recommendations and realistic constraints on the usage of this technology. Finally, in the appendix, we provide specifics on the methodology of our project.

RESULTS AND DISCUSSION

Before any parameters were varied, we verified our model by demonstrating that expected temperature profiles were obtained when the model was run for steady-state.

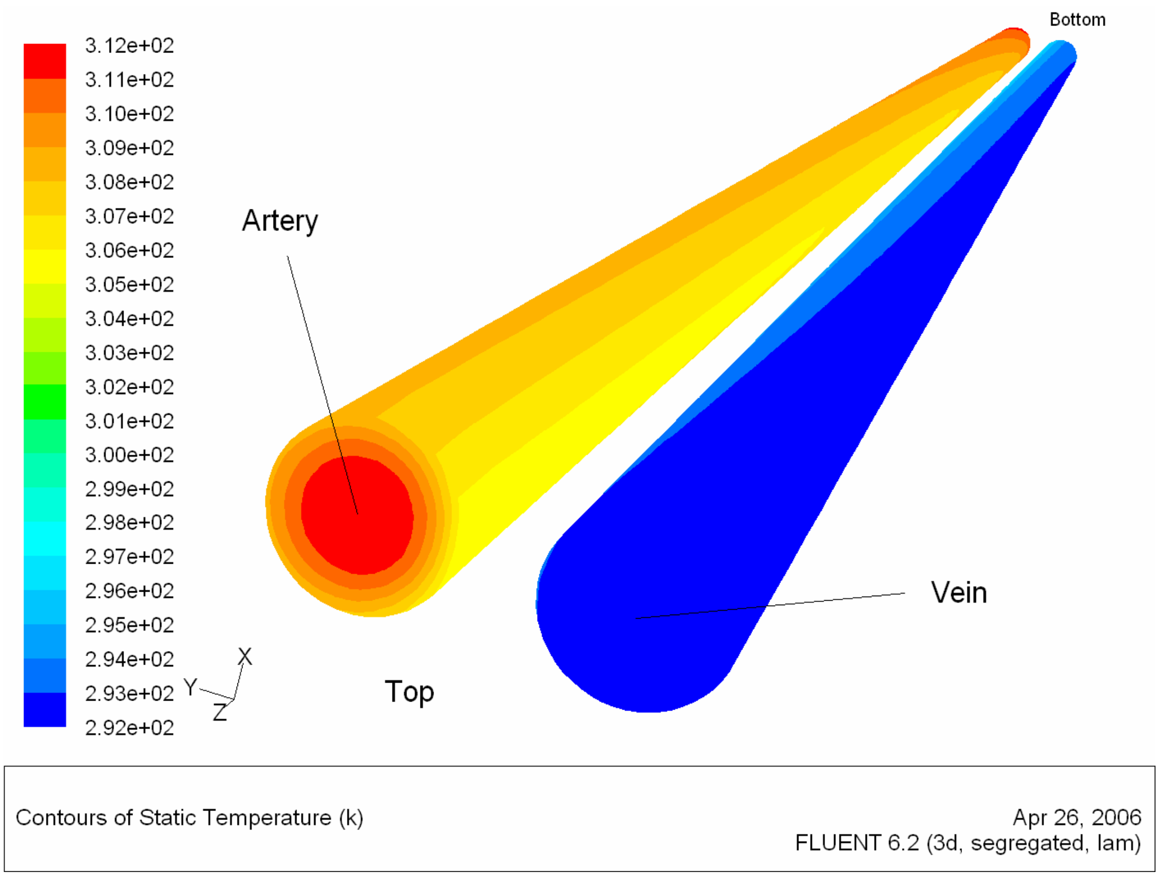

Figure 3: Static temperature contours of artery and vein

The temperature of the arterial blood steadily dropped from 37°C as it passed through the neck. As shown in figure 3, the arterial blood exhibits two temperature profiles, a concentric profile with the warmer blood at the center of the vessel, and an axial profile in which the blood is cooler closer to the countercurrent vein. These results are indicative of countercurrent exchange. The observed concentric temperature profile likely resulted from the loss of heat from the arterial blood to the surrounding neck tissue by convection. The axial temperature profile is likely caused by the countercurrent heat exchange with the cooler venous blood. This is further supported by the fact that the profile is much more pronounced at the top of the neck than the bottom.

According to Zhu et. al, the arterial blood temperature decay is a function of the blood flow rate, the neck surface temperature, and the temperature of the countercurrent venous blood. In order to compare the results of our simulation with

Zhu's theoretical model, we varied these parameters as well. To compare our results with Zhu's we measured arterial outlet temperature by taking surface integral weighted averages.

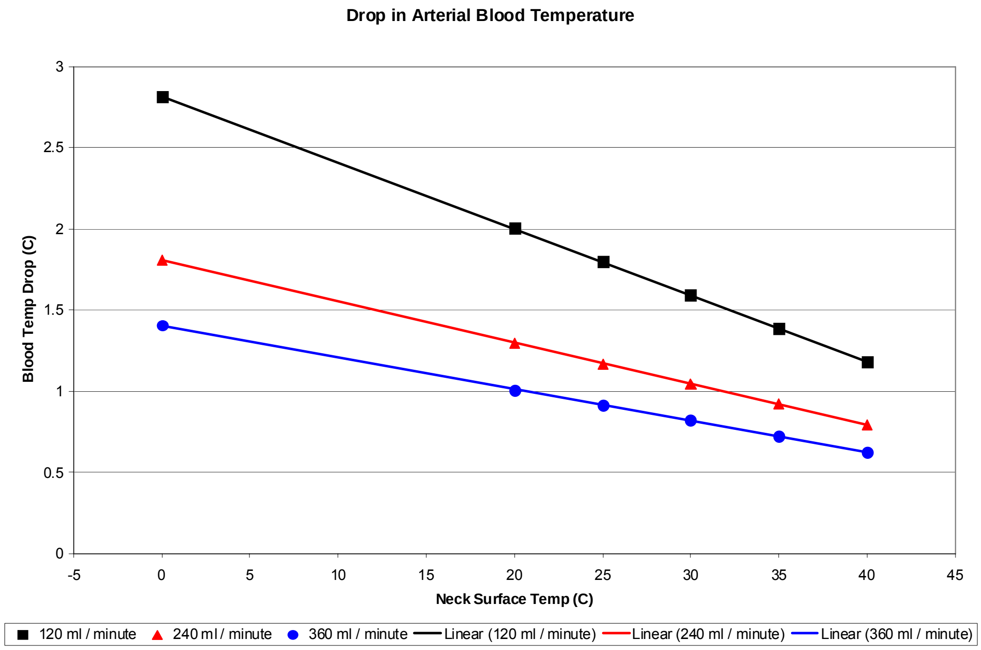

Figure 4: Arterial temperature drop for 19°C inlet temperature and various flow rates.

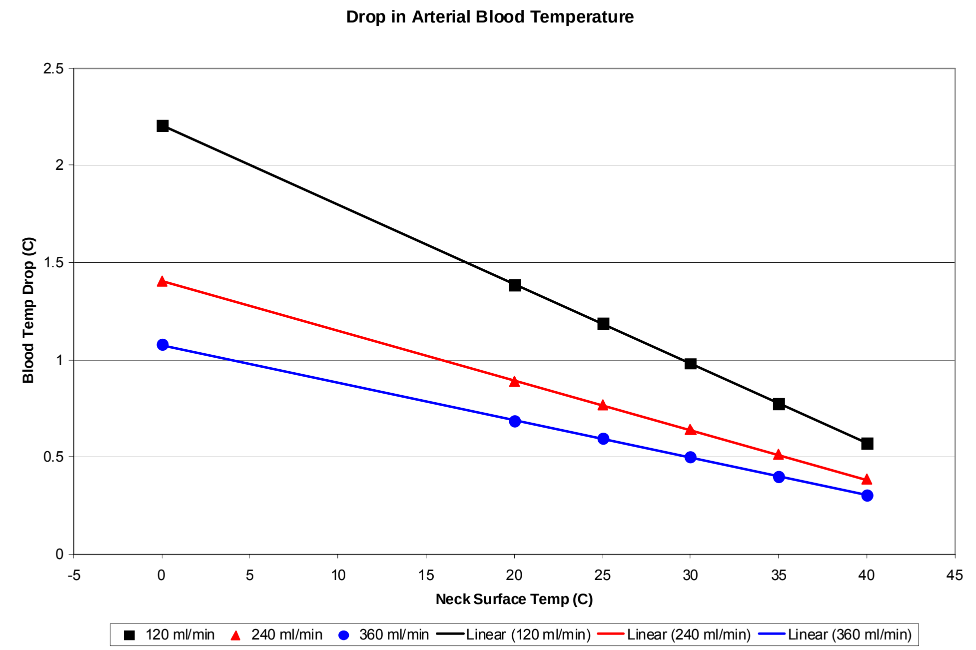

Figure 5: Arterial temperature drop for 29°C inlet temperature and various flow rates.

As seen in figures 4 and 5, the arterial blood temperature drop varies inverse- linearly with the neck surface temperature, for both 19°C and 29°C venous blood inlet temperatures and all flow rates. The greatest drops occurred at a neck surface temperature of 0°C and the smallest drops occurred at 40°C neck surface temperature. Furthermore, the amount of temperature decay diminishes with higher flow velocities, likely due to the decreased time for heat exchange to occur. The largest drop in arterial temperature observed in our simulations was 2.8°C, at 0°C neck surface temperature, 120 ml/minute blood flow rate, and 19°C venous inlet blood temperature.

In comparison to results from Zhu et. al, our results generally show a higher level of temperature drop. For example, Zhu's calculations indicated a 1.1°C arterial temperature drop at a neck surface temperature of 20°C, flow rate of 120 ml / minute and venous temperature of 19°C while our simulation suggested a 2.0°C drop with the same parameters. There are also differences of 0.2°C to 0.9°C in the resulting arterial temperature between the two models for the other tested values. However, the trends observed in the temperature decay, relative to neck surface temperature and blood flow rate, are identical between the models.

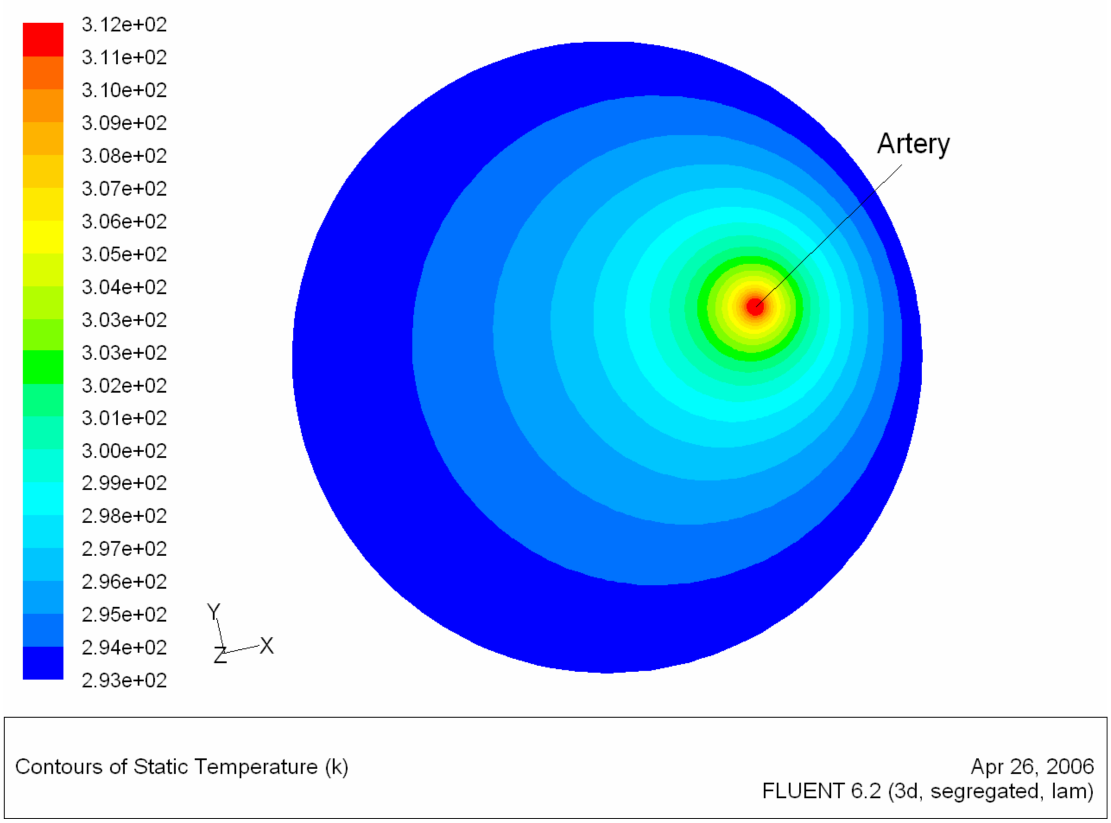

Figure 6: Contours of Static Temperatures without Vein

Finally, in order to isolate the effects of the counter-current heat exchange between the artery and the vein, we ran simulations with the venous blood flow removed and tested for the effects of just heat convection to the tissue on the arterial blood temperature.

Without the effects of the vein, the heat from the artery diffused by convection into the surrounding tissue. This resulted in the circular temperature profile seen in figure 6. These “vein-less” simulations were performed for all neck surface temperatures and flow rates, and we considered them as controls to measure the effects of countercurrent heat exchange.

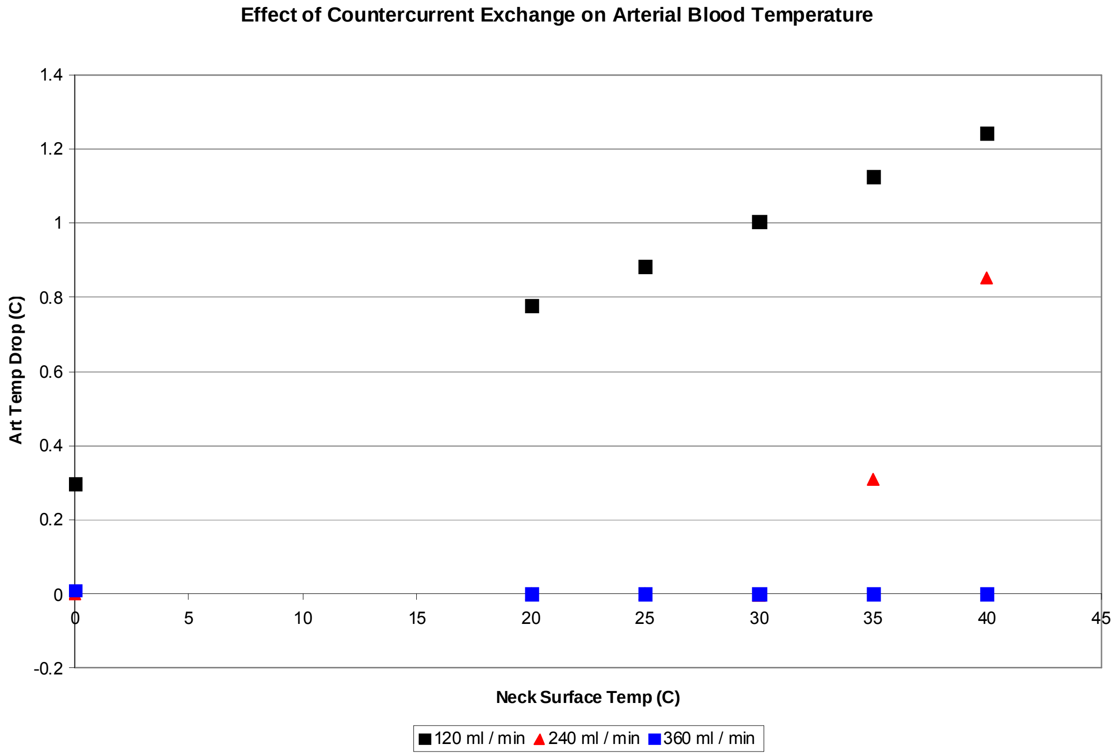

Figure 7: Effect of Countercurrent Exchange on Arterial Blood Temperature

The observations from our initial model (with vein), when compared with the control model (“vein-less”), resulted in a measure of only the effects of countercurrent heat exchange on the arterial blood temperature, as seen in figure 7. At 120 ml/minute flow rate, the relationship between the effects of countercurrent heat exchange is fairly linear with the neck surface temperature, with the most effect of 1.24°C drop at 40°C neck temperature. At higher flow rates, however, the effect of the countercurrent heat becomes much less significant when compared with the convective heat exchange between the neck and tissue. In fact, in our simulation for 360 ml/minute flow rate and neck surface temperatures between 0°C and 30°C for 240 ml/minute flow rate, the effect of the countercurrent heat exchange on the arterial blood temperature is essentially zero.

This result demonstrates that the efficiency of the countercurrent heat exchange used in many biological systems is highly dependent on the blood flow rate. According to Zhu et. al, the blood flow rate for the external carotid artery in the average adult human can vary between 75 to 270 ml/minute, and can increase by approximately 30% after moderate muscular exercise. Therefore, the resting state of the body and the blood flow are also important factors to consider in brain cooling. However, in their model Zhu et. al did not consider the effects of countercurrent heat exchange separately from convection, and direct verification of our results was not possible.

Sensitivity of Simulation to Material Property Values

Although we used the property values of viscosity, thermal conductivity, specific heat and density used in Zhu's analysis, we checked the sensitivity of our model to variations in these parameters, since it is clear that properties used by Zhu were approximate figures for tissue and blood.

Since the ranges for these types of values in humans are difficult to find, we varied the parameters by twenty percent to observe sensitivity. When density of tissue and fluid were varied from 800 to 1200 kg/m^3 we found that the arterial temperature drop was negligible at under a few thousandths of a degree (Appendix C, Figure C.1). Similarly varying fluid viscosity from .0021 kg/m-s to .0033kg/m-s negligibly affected the temperature drop by a few hundredths of a degree.

Varying the specific heat of the blood and varying the thermal conductivity of the tissue resulted in variations of nearly .6°C (figure 8 and figure 9). However specific heat of the tissue and the thermal conductivity of the fluid resulted in minimal variation of arterial temperature drop. Thus, it is important to find accurate values for specific heat of blood and the thermal conductivity of tissue when modeling heat loss in the neck.

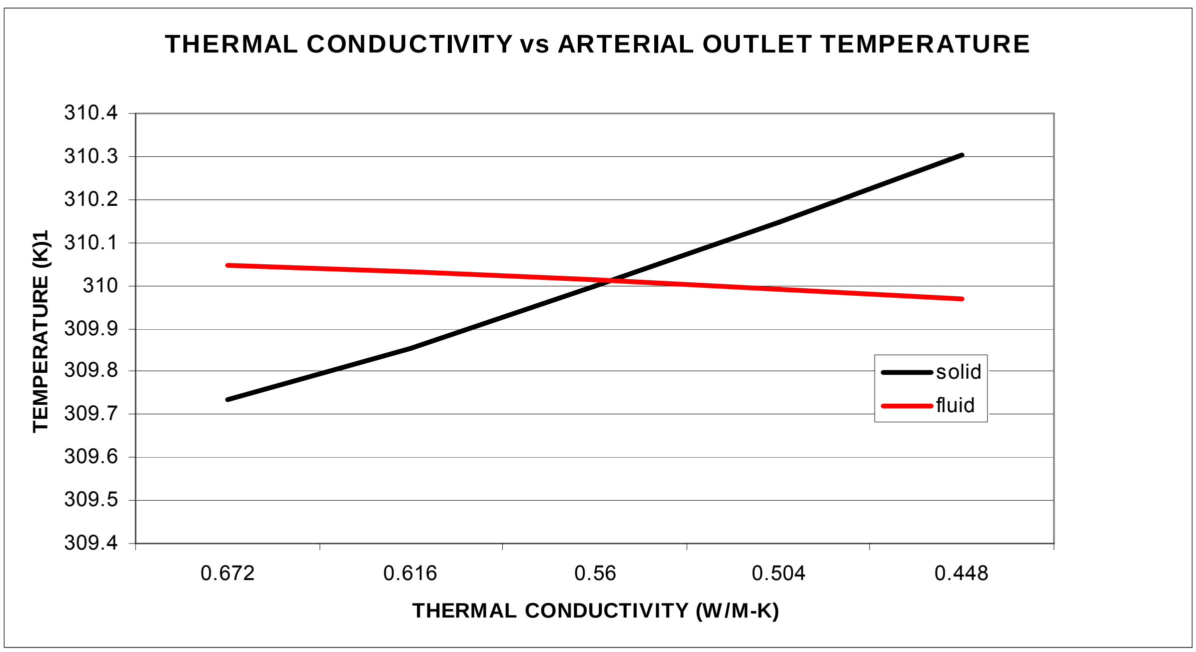

Figure 8: Sensitivity Analysis of Temperature drop to Thermal Conductivity

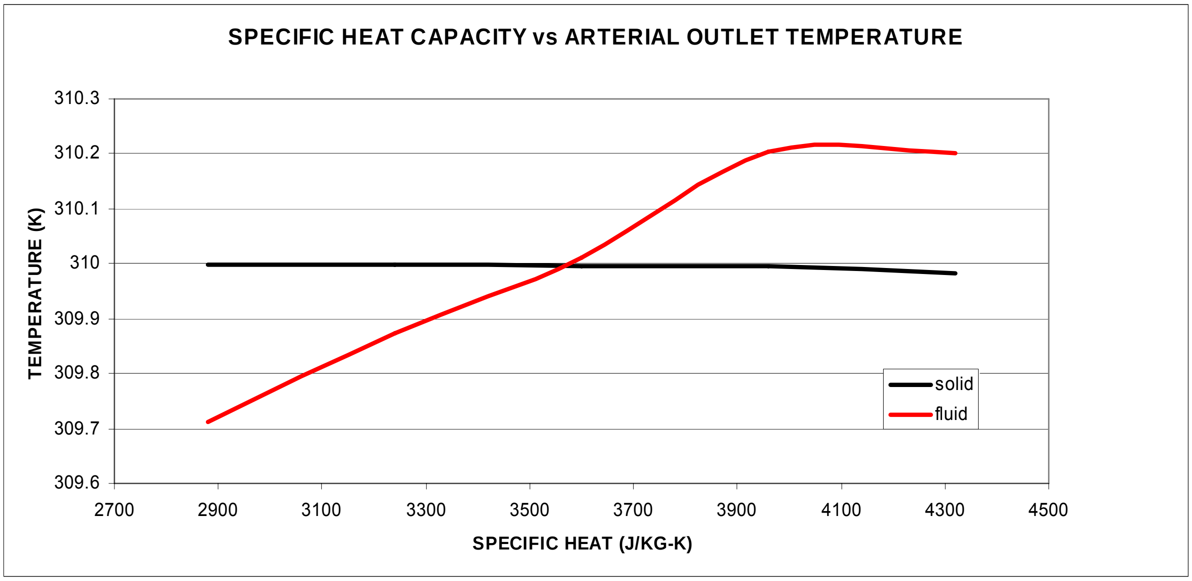

Figure 9: Sensitivity Analysis of Temperature drop to Specific Heat

CONCLUSION

During fever and hyperthermia, the core body temperature can reach upwards of 42°C, which can damage the heat-susceptible cerebral tissue. Therefore, the countercurrent heat exchange system between the carotid artery and the jugular vein may exist as a mechanism to protect the brain from hyperthermia. With ambient skin temperature (25°C) and normal blood flow rate (120 ml/min), our model demonstrates that the average temperature of the arterial blood reaching the brain drops by 1.18°C while traveling through the neck. The effect of the countercurrent exchange alone contributes 0.88°C to this temperature decay. Placing an ice pack on the neck surface can further decrease the arterial blood temperature by as much as 1.0°C and can serve to protect the brain from reaching lethal temperatures. At lower neck surface temperatures or higher blood flow rates, however, the neck surface temperature becomes the dominant effect on the arterial blood temperature drop and the effect of countercurrent heat exchange becomes minimized.

In short, the following observations were made.

The overall temperature drop of blood between the inlet to the carotid artery and the outlet:

- Decrease with increasing blood flow rates
- Decrease with increasing neck surface temperature
- Increase with increasing carotid vein inlet temperature

The temperature drop due to the isolated effects of counter current heat exchange in the same region:

- Decrease with increasing blood flow rates and was negligible for higher blood flow rates
- Increase with increasing neck surface temperature

Based on these observations:

Though a trend in the temperature drop is apparent for different values of the variables considered, this trend only holds within the ranges considered in our study and values outside this range would very well, if not definitely, deviate from the trend. Hence, the recommendations above hold only for conditions within these ranges as well.

Our study was quite literally a direct replication of Zhu's study in many respects. The main difference was the method used i.e. analytical versus computer simulation. Zhu's results were identical to ours qualitatively. However, there were significant quantitative differences observed. The maximum carotid arterial temperature drop which was observed for a blood flow rate of 120 ml/min with a neck surface temperature of 20°C and vein inlet blood temperature of 19°C was about 1°C for Zhu's analysis while our analysis showed a drop of 2°C (twice as much!). This may be attributed to the fact that we used an inter-vessel spacing of 7 mm compared to 6.2 mm used by Zhu. This makes intuitive sense, though it is hard to predict exactly how much of a difference this would make. Zhu's study showed a temperature drop of 0.35°C at a blood flow rate of 240 ml/min with vein inlet blood temperature at 29°C and neck temperature at 19°C whereas ours showed a temperature drop above 0.85°C for the same inter-vessel spacing (7 mm). This suggests that the simulation showed a much larger temperature drop compared to the analytical method.

Design Recommendations

Our results show that icing the neck could aid in selective brain cooling. Thus, products could be designed to cool the necks of medical patients suffering from hyperthermia. In addition, since increased flow rate increased the arterial temperature drop, methods of stimulating flow rate could be devised to aid selective brain cooling. However, increased flow rates could result in more heat flow and should be studied further. In short:

During hypothermia, where minimal temperature drop is desirable:

- maintain maximal neck surface temperature (without incurring burn injury)
- maintain elevated levels of blood flow

During hyperthermia, where maximal temperature drop is desirable:

- maintain minimal neck surface temperature (without freezing tissue)
- maintain minimal blood flow levels

These recommendations make intuitive sense. Applying heat and exercising elevate blood temperature which would make sense during hypothermia while cooling and resting would maintain low blood temperature which would make sense during hyperthermia.

Note the ranges of blood flow rates, carotid vein blood inlet temperatures, neck surface temperatures as well as the relative difference between these and the arterial blood temperature tested. Though a trend in the temperature drop is apparent for different values of the variables considered, this trend only holds within the ranges considered in our study and values outside this range would very well, if not definitely, deviate from the trend. Hence, the recommendations above hold only for conditions within these ranges as well.

REALISTIC CONSTRAINTS OF DESIGN

Health and Safety: Some realistic constraints arise in the application of our design to the field of medicine. As our model contains several simplifications, it should only be used as an example of the phenomenon of counter current exchange and conduction in arterial blood temperature drop. Since it neglects certain characteristics of necks such as metabolic heat generation and several other blood vessels, the results should not be used to determine patient treatments or to design biomedical devices. Our results, however, could act as a guide for further work into the mechanism of countercurrent exchange in the neck.

To address some of the realistic constraints of our design, this project could be expanded upon by considering more variations in geometry. This would allow for a better model of the true behavior of heat flow in the neck. For example the follow geometry variations could be considered:

- Center-to-Center Spacing
- Vessel Eccentricity
- Vein and Artery radii
- More Accurate Schematic

In addition, heat generation could be considered in the governing equation.

Manufacturability: If a product was being designed to cool the neck, safety issues of exposing skin to cold temperatures should be taken into account. In our simulation, we modeled the neck at zero degrees which would in fact freeze skin tissue. A product would have to be manufactured that maintains the neck at a comfortably cold temperature while being comfortable to wear as well.

Software: The simulation for this project was initially done in FiDAP but we switched to Fluent after having some difficulties in FiDAP. First, Fluent is designed specifically for fluid flow problems, making our simulations run smoother and more intuitively. Once running on FLUENT, it was easy to debug any issues. Other issues that came up and are common restraints are units errors and working in complex geometries. In addition, software would lag when using networked hard drives because they were too small.

Appendix A

Geometry:

The length of the neck was set to be 250mm with a radius of 60mm. The distance to artery was set to be 30mm. As can be seen on figure A.1b, the radii of both the artery and vein were set to be 2.5mm while the spacing in between the two vessels was 7mm.

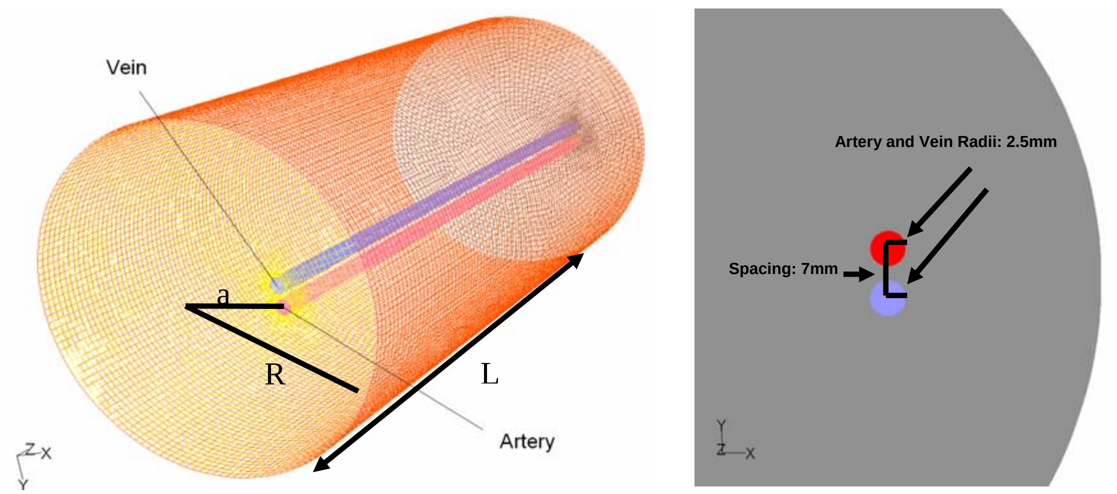

Figure A.1: a. 3D schematic of neck b. Cross section of a. Variable definitions follow:

Variable	Dimension
neck center to vessel (a)	30 mm
neck radius (R)	60 mm
neck length (L)	250 mm
vessel spacing	7 mm
vessel radius	2.5 mm

Blood flow and Temperature:

1. The arterial inlet temperature ‘Tai’ is set as 39 degrees
2. The vein inlet temperature ‘Tvi’ is varied between 19 and 29 degrees
3. The temperature of the surrounding tissue ‘Tt’ will be varied between 19 and 37 degrees
4. Blood flow rate ‘Q’ assumed constant in both vessels and varied between 120ml/min and 360ml/min which equates to blood velocity ‘Ua = Uv’ between 0.102m/s and 0.306m/s

Thermal Properties:

1 Density of blood/tissue ‘ρb = ρt’ assumed to be equal to density of water = 1000 $\frac{kg}{m^3}$

2 Specific heat capacity of blood ‘Cb’ is assumed to be equal to that of water = 3600 $\frac{J}{kg \bullet K}$

3 Thermal conductivity of blood and tissue ‘Kt = Kb’ assumed to be equal at 0.56 $\frac{J}{m \bullet K}$

4 α = 1.56E-7 $\frac{m^2}{s}$

Summary of Properties:

Geometric Properties:	Thermal Properties:
Radius of artery/vein: 2.5 mm	K = .56 L/(Kg K)
Neck radius: 60mm	p = 1000 Kg/ m^3
Length of vessel: 250 mm	Cp = 3600 J/(Kg K)
Distance between Artery and Vein: 6.2 mm	

For Tissue:
Steady State heat conduction with no convection nor generation

$$\left(\frac{\partial^2 T}{\partial x^2}\right)+\left(\frac{\partial^2 T}{\partial y^2}\right)+\left(\frac{\partial^2 T}{\partial z^2}\right)=0$$

For Blood:
Steady-State heat conduction with convection no generation:

$$\left(\frac{u\partial T}{\partial r}\right)+\left(\frac{v\partial T}{\partial y}\right)+\left(\frac{w\partial T}{\partial z}\right)=\frac{K}{p\,C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)$$

Momentum Equation for x velocity, with no gravity:

$$\rho\left(u\frac{\partial u}{dx}+v\frac{\partial u}{\partial y}+\frac{w\partial u}{\partial r}\right)=\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{\partial p}{\partial x}$$

Parabolic Velocity Profile: (see Appendix C. Figure C.4 for image and UDF file)

$$u=u_{\max}\left(1-\frac{r^2}{R^2}\right)$$

Continuity Equation with constant density:

$$\frac{du}{dx} + \frac{dv}{dy} = 0$$

Boundary Conditions:

Temperature of neck	0, 20-40 °C
Temperature of artery	39 °C
Temperature of vein	19 °C, 29 °C
Blood Flow Rate	120, 240, 36 ml/min
Zero Heat flux on faces of cylinder	

Geometric Properties:

Radius of artery/vein:	2.5 mm
Neck radius:	60mm
Length of vessel:	250 mm
Distance between Artery and Vein:	6.2 mm

Thermal Properties:

K = .56 L/Kg K
ρ = 1000 Kg/ m^3
Cp = 3600 J/(Kg K)

The thermal properties were set to be the same as those of water. These Properties were used for both the blood and the tissue.

UDF FILE FOR PARABOLIC VELOCITY:

```
#include "udf.h"

DEFINE_PROFILE(art_profile,t,i)
{
  real x[ND_ND];                /* this will hold the position vector */
  real xcor,ycor;
  face_t f;

  begin_f_loop(f,t)
    {
      F_CENTROID(x,f,t);
```

```
    xcor=x[0];
    ycor = x[1];
    F_PROFILE(f,t,i) = 0.2037*(1 - ((xcor-0.03)*(xcor-0.03)+(ycor-0.0035)*(ycor-
0.0035))/(0.0025*0.0025));
  }
 end_f_loop(f,t)
}


DEFINE_PROFILE(vein_profile,t,i)
{
 real x[ND_ND];              /* this will hold the position vector */
 real xcor,ycor;
 face_t f;

 begin_f_loop(f,t)
  {
    F_CENTROID(x,f,t);
    xcor=x[0];
    ycor = x[1];
    F_PROFILE(f,t,i) = 0.2037*(1 - ((xcor-0.03)*(xcor-
0.03)+(ycor+0.0035)*(ycor+0.0035))/(0.0025*0.0025));
  }
 end_f_loop(f,t)
}
```

NB: Highlighted value above:

- 120ml/min = 0.2037
- 240ml/min = 0.4074
- 360ml/min = 0.6112

The inlet velocity profile for both the carotid vein and artery were assumed to be identical and fully developed and hence, parabolic. The profile was developed backwards from the mass flow rate to the volumetric flow rate from which the average z – axial velocity was obtained. Assuming a parabolic velocity profile radiating from the center of the vessel with a no-slip boundary condition at the blood-vessel interface, an area weighted surface integral was equated to the average velocity to calculate the relevant parameters (V_{max}) for each mass flow rate.

$$V_{ave} = \frac{\left[\int_{r=0mm}^{R=0.25mm} V * 2\pi r * dr\right]}{\left[\pi R^2\right]} = \frac{\left[\int_{r=0mm}^{R=0.25mm} (V_{\max}) * (1 - \frac{r^2}{R^2}) * 2\pi r * dr\right]}{\left[\pi R^2\right]} = 0.5 * V_{\max}$$

APPENDIX B

Problem Statement:

Table B.1 Problem statement settings in Fluent

Model	Setting	Explanation
Space	3D	Three dimensional fluid flow
Time	Steady	Steady state temperatures
Viscous	Laminar	Non-Turbulent flow
Heat Transfer	Enabled	Modeling heat flow during fluid flow
Solidification and Melting	Disabled	No phase changes
Radiation	Disabled	No radiation
Species Transport	Disabled	Neglect species transport

Solution Statement:

Table B.2 Equations Solved

Equation	Solved?
Flow	Yes
Energy	Yes

Table B.3 Relaxation settings

Variable	Relaxation Factor
Pressure	0.30000001
Density	1
Body Forces	1
Momentum	0.69999999
Energy	1

Table B.4 Linear Solver settings

Variable	Solver Type	Termination Criterion	Residual reduction Tolerance
Pressure	V-Cycle	0.1	.7
X-momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Z-Momentum	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7

Table B.5 Discretization Scheme settings

Variable	Scheme
Pressure	PRESTO!
Momentum	QUICK
Energy	QUICK

Table B.6 Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5e+10
Minimum Temperature	1
Maximum Temperature	5000

Time Integration Statement – not relevant because problem is steady state

PLOT OF ELEMENT MESH

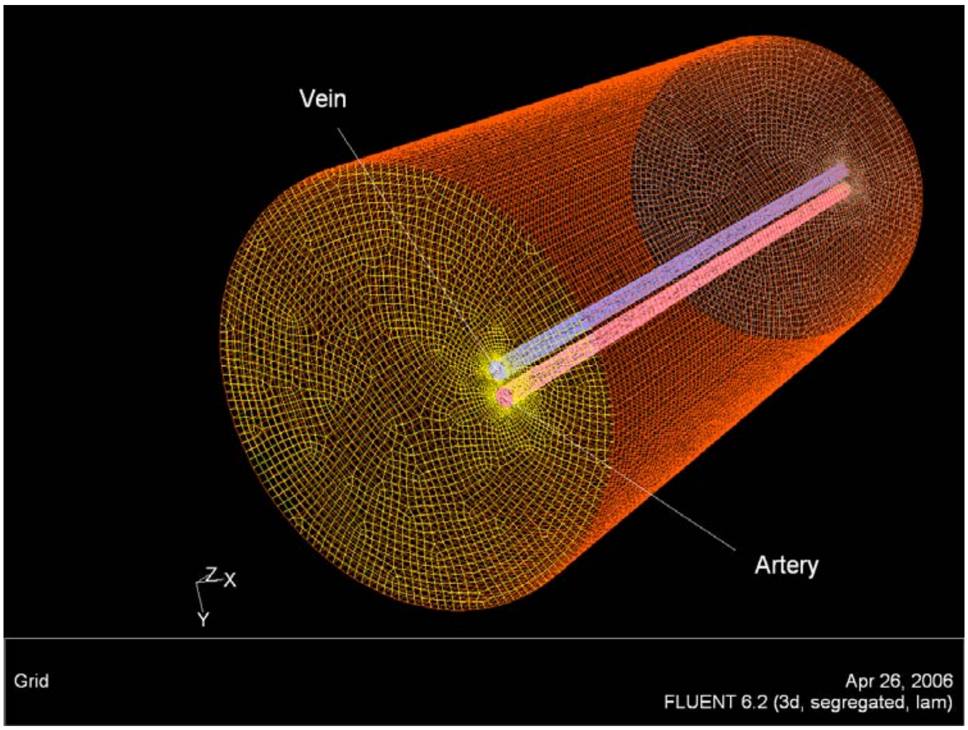

Figure B.1 Mesh generated by Gambit and plotted in Fluent. Number of nodes = 414692

MESH REFINEMENT

Since most behavior is occurring near the artery and vein a mesh with smaller nodes near the vein and artery was created to increase the accuracy and precision of our results. To do this, a growth function was specified from the surface of the artery and veins that resulted in larger nodes as distance from the artery and vein increased. Using the size function allowed for a reduction in the number of nodes than using uniformly sized small elements for the whole mesh.

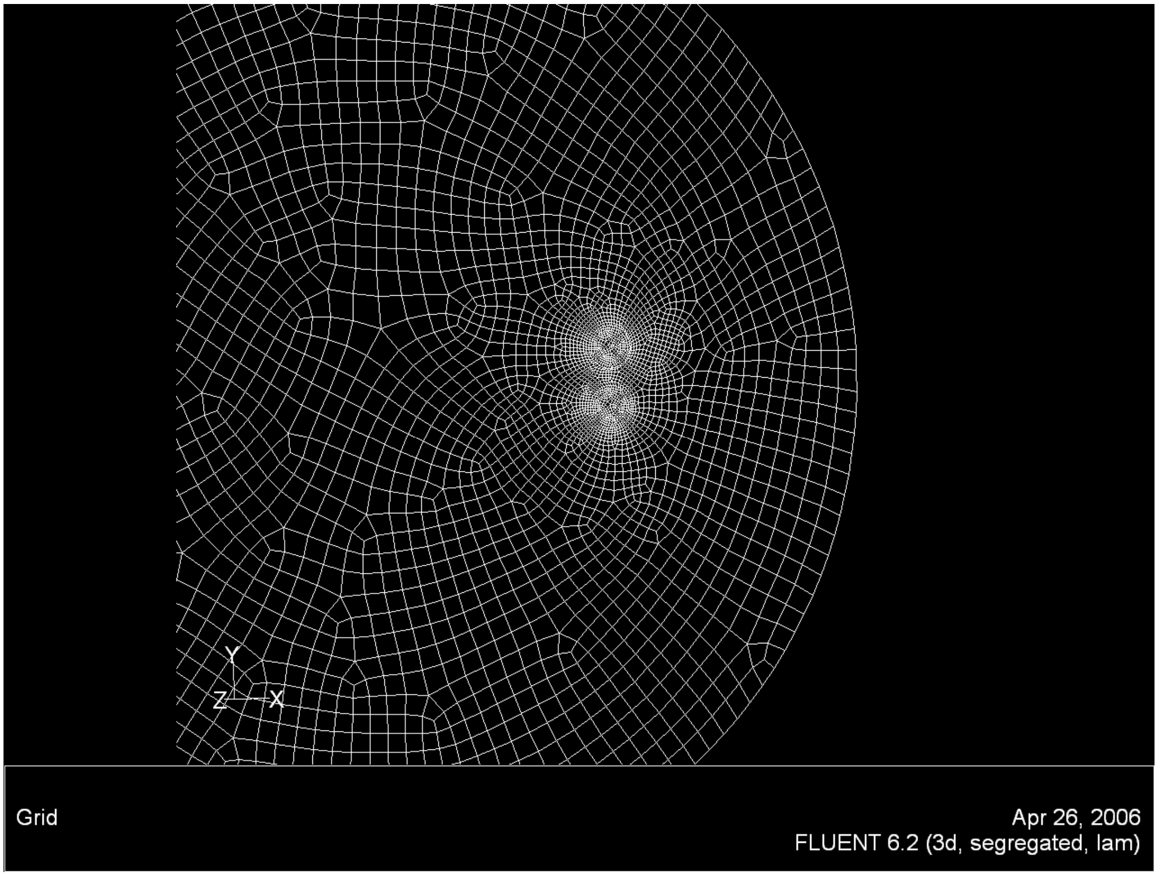

Figure B.2 Top view of mesh revealing smaller nodes near artery and vein.

Because of the difficulty in re-meshing 3D geometry, instead of testing for mesh convergence, we made sure to begin with a mesh that had enough nodes as well as contained high quality elements. From examining the mesh in GAMBIT all elements were well under quality .65 (Appendix C figure C.3).

CONVERGENCE OF SOLUTION

We used a strict convergence criteria of 1e-6 to ensure convergence. Figures B.3 and B.4 show that the criteria was adequate for energy, continuity and velocity.

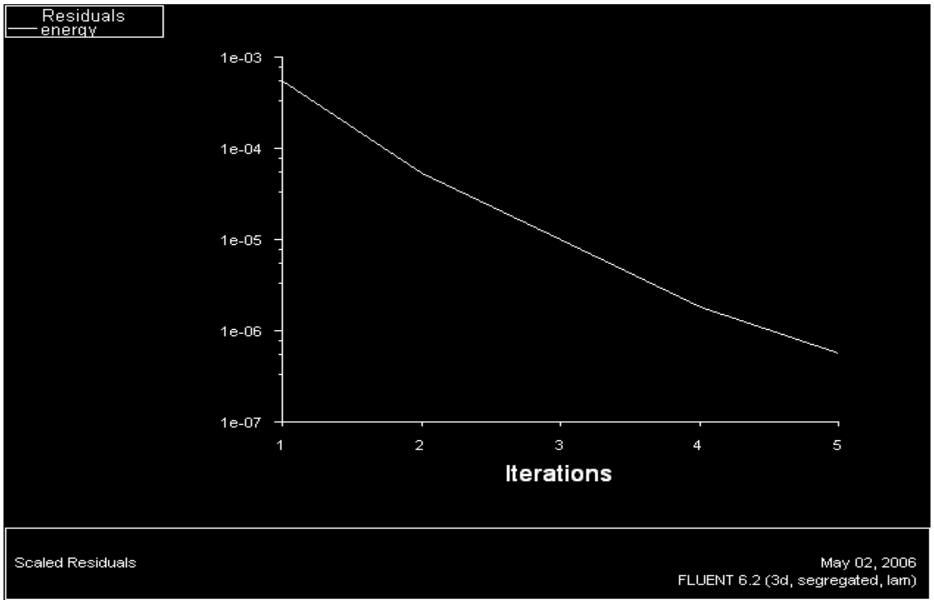

Figure B.3 : Scaled energy residuals per iteration

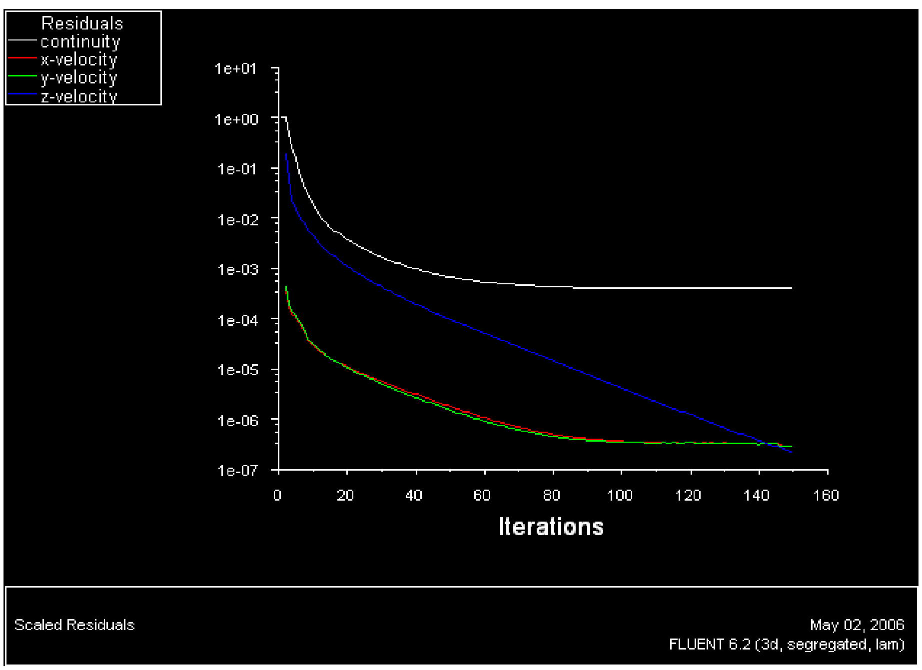

Figure B.4 : Scaled velocity and continuity residuals per iteration

APPENDIX C

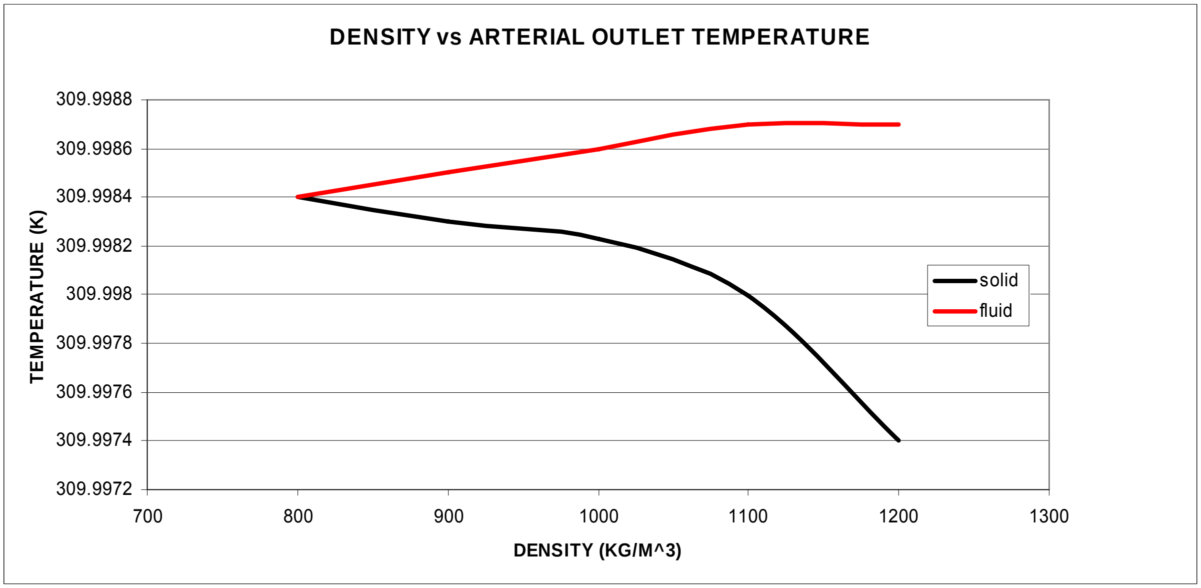

Figure C.1 : Sensitivity Analysis of Temperature drop to density

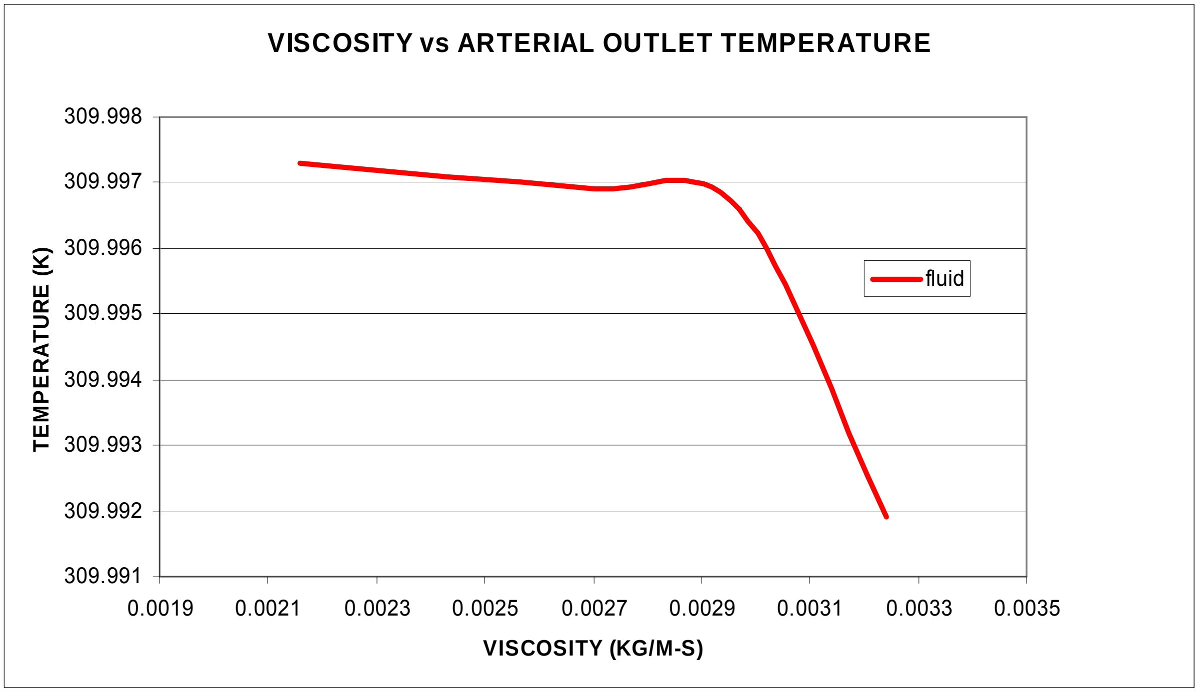

Figure C.2: Sensitivity Analysis of Temperature drop to Viscosity of blood

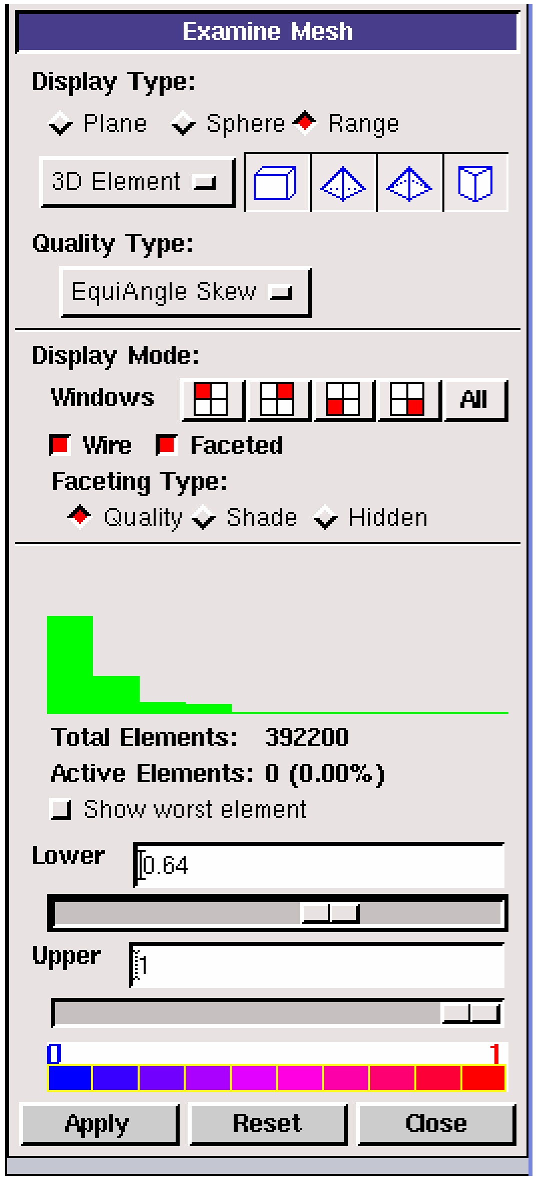

Figure C.3: Examine Mesh feature in FiDAP reveals all elements beyond quality level 0.64

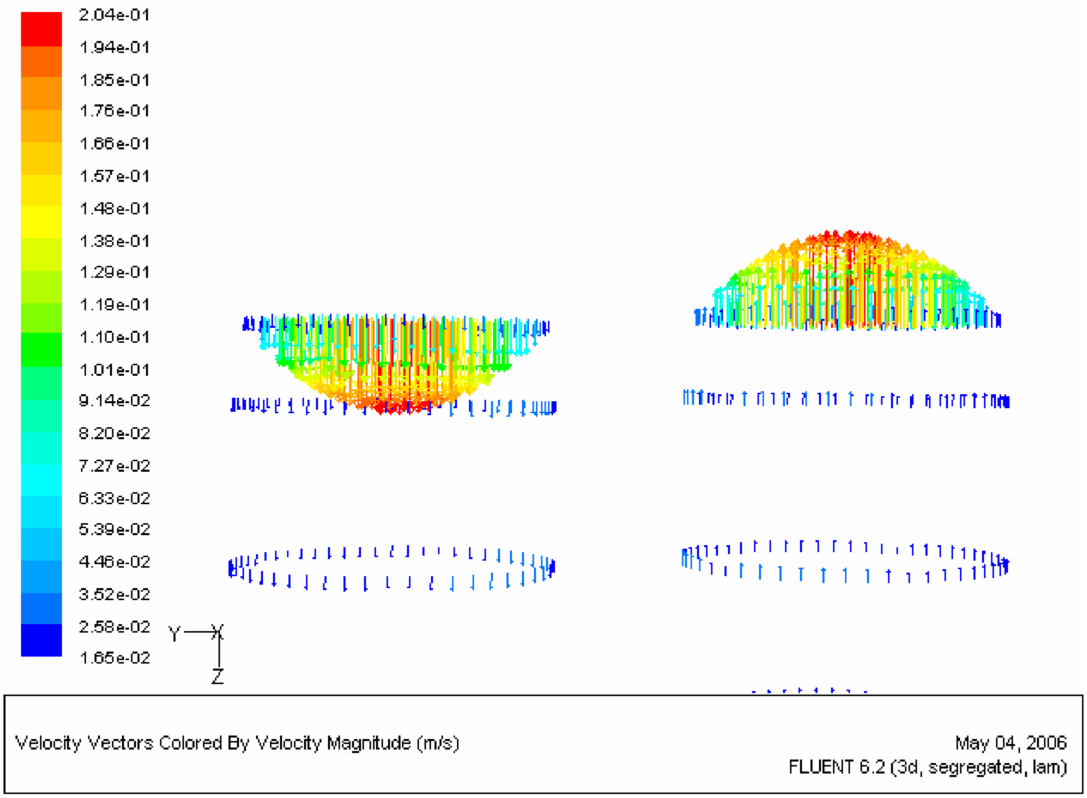

Figure C.4: Velocity Vectors at flow rate of 120ml/minute

Appendix D -- References:

Datta, A.K. 2002. *Biological and Bioenvironmental Heat and Mass Transfer*. Marcel Dekker, Inc, Dept. of Biological and Environmental Engineering, Cornell University, Ithaca, New York.

Datta, A.K. 2004. *Computer-Aided Engineering: Applications to Biomedical Processes*. Dept. of Biological and Environmental Engineering, Cornell University, Ithaca, New York.

Zhu, Liang. January 14th, 2000. *Theoretical Evaluation of Contributions of Heat Conduction and Countercurrent Heat Exchange in Selective Brain Cooling in Humans.* Biomedical Engineering Society.