

# **The ABC's: Atherosclerosis, Blood Flow, and the Carotid Artery**

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## **Executive Summary:**

The effects of blood flow were analyzed in the carotid artery, using computer aided engineering software (FIDAP and GAMBIT). The study was conducted because patients that have atherosclerosis often have plaque build up on the interior walls of the carotid artery directly before bifurcation. The design objectives were to analyze the velocity and shear stress through the carotid artery as the common section splits into the external and sinus sections. The results obtained demonstrated minimal velocity and shear stress in both the sinus and external sections of the artery. These differ from the expectations. In reality neither velocity nor shear stress decrease to this extent in normal blood flow through arteries. The results should have shown a decrease in both velocity and shear stress directly before the bifurcation. The plots obtained did demonstrate decreased velocity near the interior walls of the artery, as expected. Errors in the results relate to numerical problems with meshing. Further studies should be conducted to improve upon these results and include more realistic, less simplified parameters.

## Results and Discussion

Figure 2 shows the velocity vector plot of the carotid artery model. As seen in this diagram, the velocity was lower in the carotid sinus and the external carotid than in the common carotid. It appeared to decrease gradually from a maximum value at the inlet to a minimum value at the outlet. The velocity was especially low in the smaller branch, the external carotid, where the velocity appeared to reach zero in the entire cross-section of the branch's end. The velocity was also lower at the artery wall than in the center of the flow, as would be expected with the no-slip condition of zero velocity at the artery walls.

Figure 3 is the shear rate contour plot of the carotid artery model. From this diagram, one can see that the shear stress also had drastically lower values in the carotid sinus and external carotid than in the common carotid. Shear was at a maximum at the walls of the inlet, then remained high at the walls throughout. Shear appeared to decrease gradually from the maximum value at the inlet to a minimum value at the outlet. Like the velocity, the shear was also zero in most of the external carotid.

The results that were expected were similar shears and velocities in each artery branch, with lower values for both at the walls near the bifurcation. These results were not found, but the actual results were not realistic. The actual results were unrealistic for two reasons: velocity and shear do not decrease as drastically in practice and velocity and shear do not reach zero across an artery branch in practice.

In order to make the model more realistic, we tried numerous fixes. First, we refined the mesh in Gambit, trying meshes with smaller elements, but obtained similar results. Next, we tried assigning pressure drops across the different lengths in BCFLUX,

specifically one from common carotid to external carotid and one from common carotid to carotid sinus. Again, this method did not improve the results. A pressure penalty was added, which also did not improve upon the results. Next, we tried making the external carotid and the carotid sinus the inlets, assigning velocities to the ends of these branches. This method gave more realistic results, but they were unacceptable because the velocities were pointing the wrong direction. In the end we were unable to improve upon these results.

## **Conclusions and Design Recommendations**

The results obtained of velocity vectors and shear stress in an average male carotid artery were not what we had anticipated. Although, we can explain why they are incorrect, the exact reasons are due to numerical computing issues that need to be more closely studied.

The velocity should not slow down as much as our results shown in the external and sinus sections of the artery (see figure 2). The velocity should be slower on the outer edges directly before the bifurcation. The velocity is correct in our result on the inside edges of the artery. Here, like expected, the velocity is nearly zero due to the no-slip boundary condition as related to normal flow in a pipe.

The shear stress should be smaller at the edges right before the bifurcation (Perktold and Rappitsch, 1995). This is not the case in our contour of shear stress.

Overall, the design recommendations we give are to spend more time on the meshing step. The reason FIDAP is giving incorrect results is due to the meshing done in

GAMBIT, which used tetrahedral elements. There seems to be an accuracy problem involved with this type of meshing. Suggestions to improve upon this would be remeshing using edge elements. Due to the time constraints of this project, this was unable to be studied at this point in time. To get more efficient results in the future this would be the area to focus on.

We will not focus on cost considerations, since this is more of a research than commercial project.

Once the problems with the results are overcome in FIDAP one could do further research on this problem by changing some of the assumptions and adding additional parameters. For example, we assumed blood was a Newtonian fluid to simplify the project, when in reality it is not. This could be incorporated into a new study. Also, blood is not flowing steadily throughout the body like we assumed, but is pulsatile. One may also wish to study what effect changes in diameter of blood vessels would have on the velocity and shear stress. An increase in shear stress and velocity would be expected in the case of a decrease in diameter size, although there would be stagnation points, causing slower velocities right before the change in size. The opposite would be expected of an increase in diameter, where velocities and shear stresses would be expected to decrease. It would also be interesting to study the flow of blood through an artery that has plaque build up on the interior walls due to atherosclerosis. In this case one would expect similar changes to a decrease in diameter, because the plaque would cause the inner diameter to shrink.

Overall, additional time is required to obtain more accurate results for this study and future studies can include more complicated and thus more accurate procedures.

Perhaps a study similar to this can someday help in saving the lives of patients affected by atherosclerosis.

## **Appendix A: Mathematical Statement of the Problem**

The Carotid Artery consists of three branches: the Common, Sinus, and External branches. The dimensions of the artery were originally taken from Perktold and Rappitsch, 1995, but to obtain a successful mesh in Gambit, the geometry was simplified (See Gambit pictures). The Common and Sinus branches were approximated as equal. Their diameters were entered as 0.0066 meters, and the External branch was 0.0036 meters. An angle of 25 degrees exists between the Common axis and the Sinus axis, and an angle of 25 degrees also exists between the Common Axis and the External Axis.

When designating the initial conditions, boundary conditions, and governing equations, several assumptions were made. The artery walls were assumed rigid. The artery was approximated as isothermal system at a constant temperature of 98.6 degrees Fahrenheit, 37 degrees Celsius. The blood was approximated as a Newtonian fluid with a high shear rate, which affects viscosity. The initial conditions included a no slip condition where the velocity at the wall is zero and an inlet velocity of 0.3 meter per second was specified at the entrance of the Common branch of the artery, taken from Mechanical and Chemical Aspects of Human and Organ Tissues. No pressure specification was made. The other input parameter consisted of blood density of  $1.56 \text{ kg/m}^3$  and a viscosity of 3.0 centipoise,  $0.3 \text{ kg/m}^*\text{s}$  (Cooney, 1976).

The governing equations used to define the flow problem were the continuity equation, which conserves mass, and the momentum equation, which balances the forces acting on the system. The governing equations took the following forms:

**Continuity Equation:**  $\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0$

**Momentum**

**Equation:**  $\rho \left( \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} \right) = -\frac{\partial P}{\partial x} + \mu \left( \frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right)$

Table of Input Parameters:

<b>Input Parameter</b>	<b>Value</b>	<b>Units</b>
Inlet Velocity	0.3	m/s
Wall Velocity	0.0	m/s
Blood Density	1.56	kg/m <sup>3</sup>
Blood Viscosity	0.3	Kg/m*s
Common Diameter	0.0066	meters
Sinus Diameter	0.0066	meters
External Diameter	0.0036	meters

## Appendix C: References

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