Modelling blood flow through arterial geometry

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Atherosclerosis

Diseases within the circulatory system can be detrimental to the health of patients, who may require serious medical operations to remove or cure them. One such disease is that of plaque build up along regions of the inner lining of arterial walls, called atherosclerosis. High blood pressure can sometimes lead to the erosion of sections of the intima (inner wall layer), creating anchorage points for any plaque that has already diffused into the blood stream in patients with seriously high cholesterol levels. This can build up to a point where the flow of blood can be significantly impaired by the stenosis or narrowing of that particular arterial region. Strokes are the extreme result of this biological process.

Aims of project

Computational fluid dynamics or CFD can now be used to model complex biological geometry in conjunction with 3D imaging techniques such as MRI scanning. With help from The Royal Devon and Exeter Hospital, data on atherosclerosis in the right common carotid artery (CCA) was obtained from a single patient and used to create three fluent models. MRI scan data was taken and processed using ScanIP, ScanFE and ScanCAD to export and run these in fluent. See figure 1 for an MRI slice through patient and figure 2 for the schematic of the arterial region. These models had a series of tests conducted on them to provide pressure gradients, visualisation of laminar and turbulent boundary layers and wall shear stress values around the aforementioned geometry.

Previous work

Many researchers have recently been investigating the effects of blood flow on idealised geometry using CFD, relating specifically to arteries and veins being represented as homogonous constant diameter cylinders or curved pipes. Van Tricht, et al 2006, investigated the effects of stent shape in relation to how blood flow was effected by either a 6mm constant diameter graft and a varying diameter of 4-7mm. The blood flow properties from that journal were replicated in this project.

The mechanics of the circulation, Caro et al 1978, outlined fundamental physics and biology relevant to the understanding of many parts of the circulatory system. These included basic flow characteristics, the heart, arteries and vein profiles and pressure properties associated in dogs and the structure of microcirculations in blood flow. Most importantly was the collective agreement on using laminar flow characteristics to represent general blood flow throughout the circulatory system, specific to the region analysed in this report. No research had yet been conducted on patient specific geometry using CFD for this particular arterial region.

Experimental

Three models were created. The first showing the stenosed artery, the second showing a CAD bypass stent and the third showing effects of an endarterectomy. A bypass stent was created in Solidworks 2005 and imported into the arterial geometry in ScanCAD, visible in figure 4. An endarterectomy is an operation whereby the stenosed artery is opened up and the plaque scraped out manually. This was obtained from the post-operative data. Two sets of data were therefore used to create all three models as shown in Figure 3.

Figure 1. MRI slice through patient showing main aorta and ascending arteries

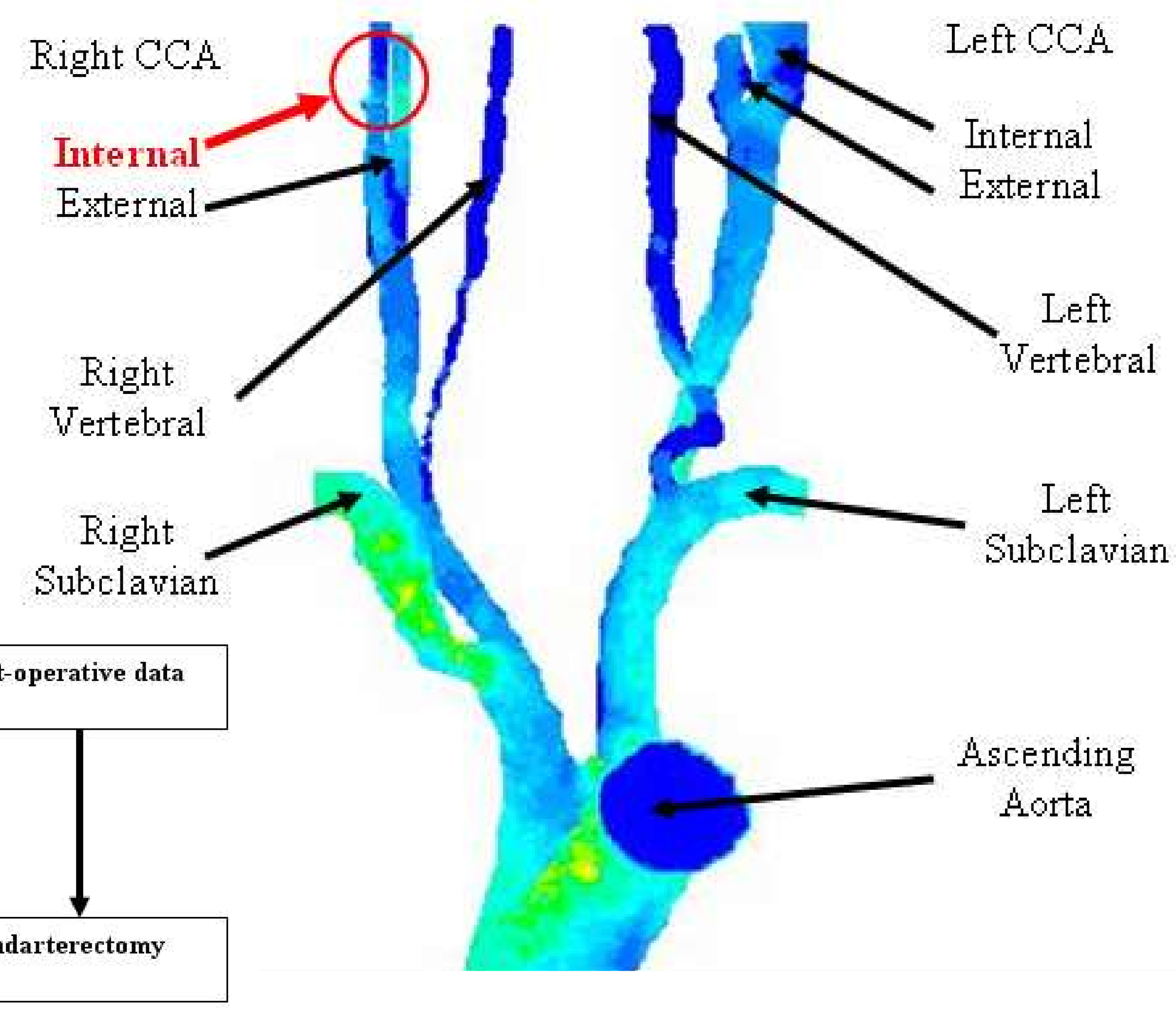

Figure 2. Bypass fluent model created from pre-operative data showing position of stenosis

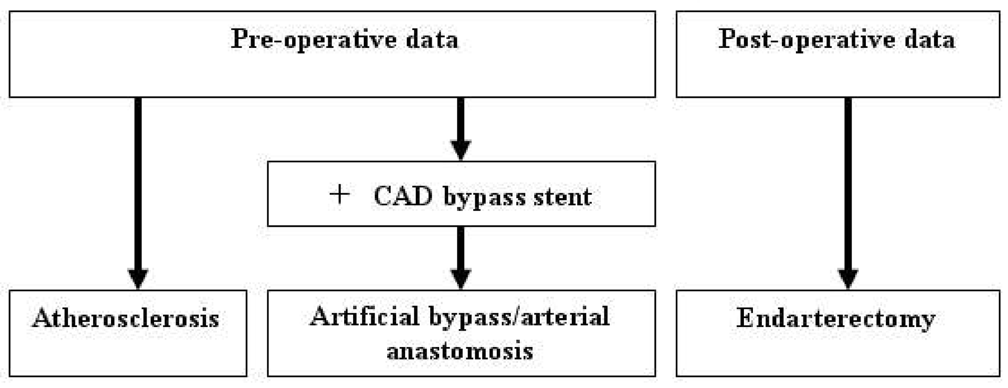

Figure 3. Diagram of layout of models from both pre and post operative MRI data sets

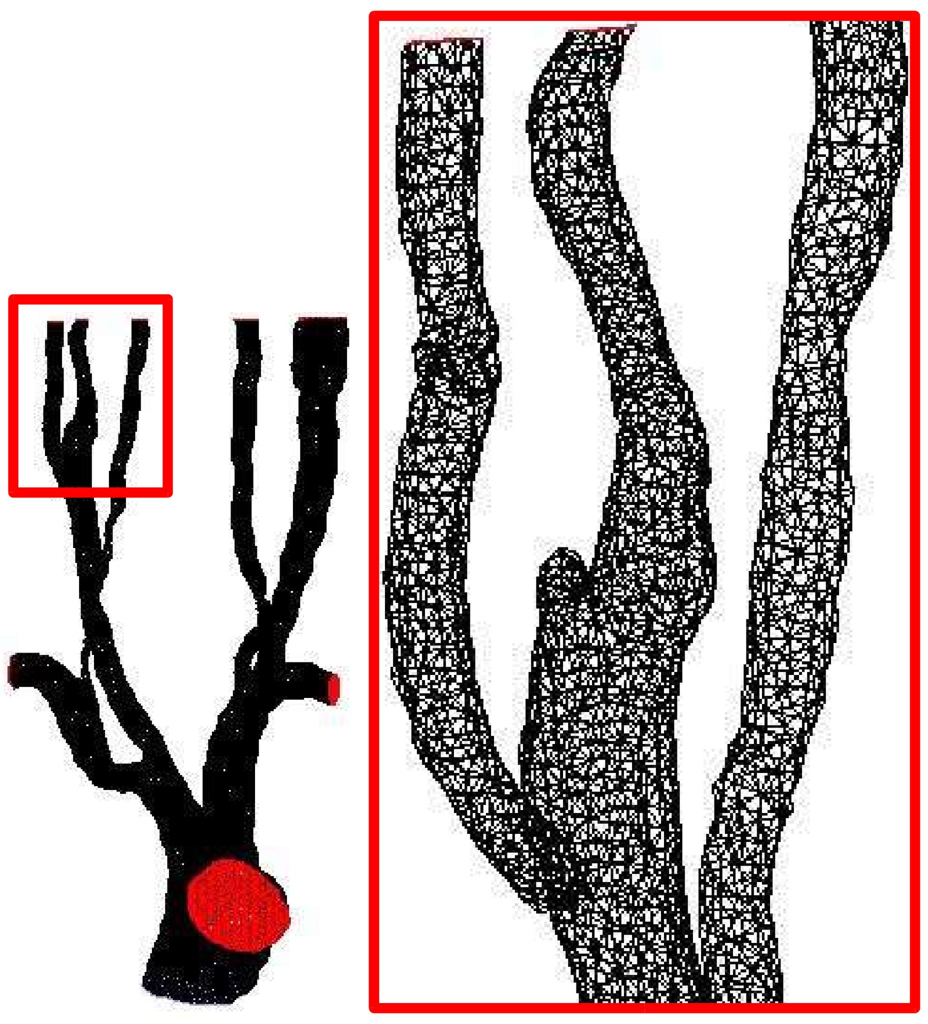

Figure 4. Mesh of second model with bypassed region enlarged. Curved bypass stent on left side

Velocity profile equation

The Poiseuille equation for laminar flow was used to create a link between the pressure changes and velocity magnitudes at the base of each model representing the heart arterial exit point. Laminar flow was considered for entrance characteristics [1]. The pulsative characteristics of a sine wave function would relate the maximum pressure change at a given point to the time step within one complete heartbeat cycle [2]. The velocity profile equation below was created purely for this project.

$$\Delta p_{local} \sin(\omega t) = 0.48 U_0^{\,2} \pi \rho$$

Where Δp_{local} was a pressure set within the systolic and diastolic pressures in Pa. U_0 is the free stream velocity from the outlet of the heart and ρ the density of the blood used within fluent. The properties of blood was likened to glycerine - water mixture with a density of 1090kgm^{-3} and kinematic viscosity of 3.44 x 10^{-6} m^{-2}s^{-1} based on van Trickt et al 2004. The heart pump pressure range was 120/80 mmHg by convention.

Discussion

The data concerning the right internal CCA in the first model was unfortunately unobtainable. Although the stenosis was visible on the pre-operative MRI scan data, it was not possible to mask in ScanIP. The resolution of the MRI scan produced a stenosis smaller in average diameter than a single pixel size. The atherosclerotic model was limited considerable by this, with the arterial section ascending from the stenosis becoming unusable owing to no fluid ever reaching it. This is why that artery stops abruptly in figures 5 and 6 for the first models. The resolution for the post-operative data showing effects of the endarterectomy was higher and thus allowed for a smoother model to be created.

Results on the atherosclerotic region in the first model identified that there was little possibility of clotting occurring along the intima. The adjoining right external common carotid artery revealed higher wall shear stress values, showing that collateral circulation was occurring to compensate for the stenosis. This was verified by a contour plot of Reynolds number, with the right external showing signs of turbulence build up. The wall shear stress surrounding the stenosis did not exceed 200Pa and therefore hemolysis did not occur.

The artery walls in the atherosclerotic region in the second model gave rise to the development of intimal hyperplasia because the wall shear stresses were less than 0.5Pa [1]. Overall dynamic pressures dropped significantly after endarterectomy in the third model, validating the elimination of the atherosclerosis from the right internal common carotid artery. The opposing common carotid artery sections were more balanced in terms of overall inner diameter values, showing the improvement of blood flow characteristics within the patient.

The resolution increased significantly in the post-operative MRI scan data as a result of limited capabilities of the pre-operative data to visualise atherosclerosis. The post-operative data thus had smoother artery walls and had a mesh density three times higher than the pre-operative. In the future, resolutions equal to that of the post-operative data would need to be used for similar computational analysis. This project was a beginning of the CFD analysis into patient specific data and thus used simplified mathematical models with laminar flow and blood being treated as a Newtonian fluid as a basis. In the future, greater detail could be used to model the structure and behaviour of the blood and the artery walls to improve the computational approximations required for actual circulatory flow.

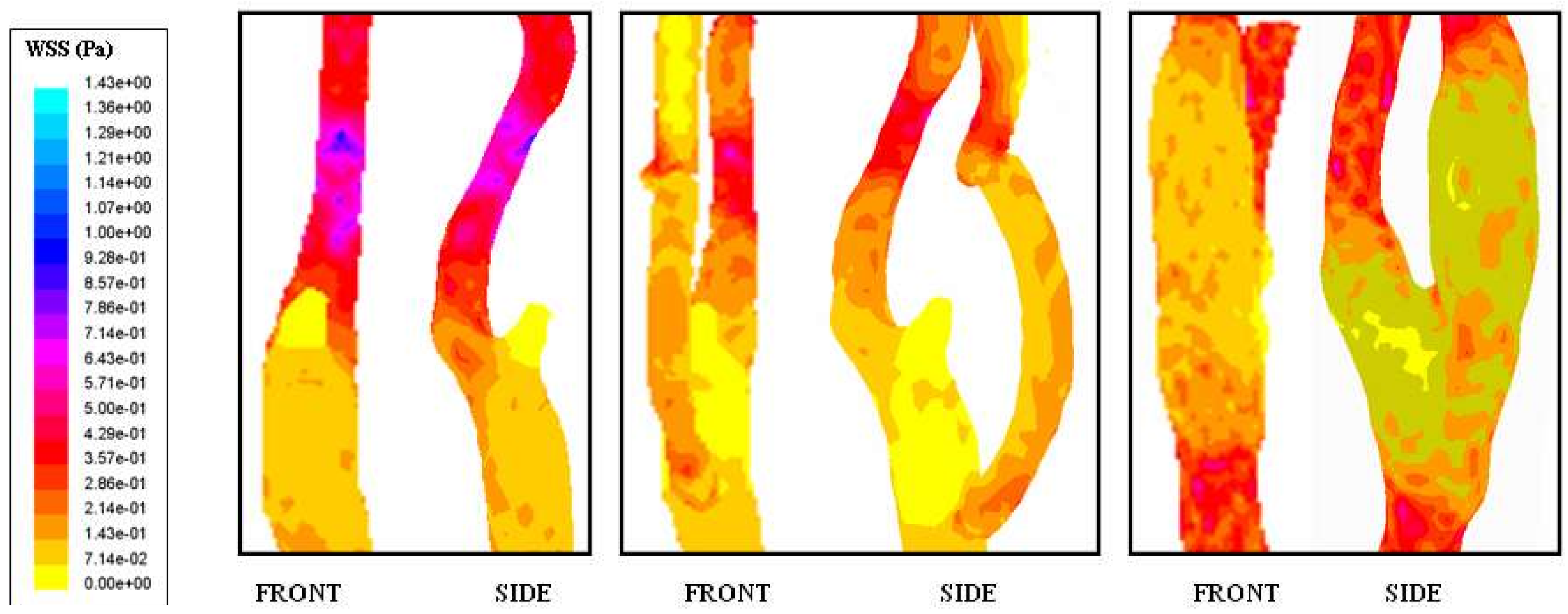

Figure 5. Wall shear stress (WSS) contour plot for models 1-3 left to right.

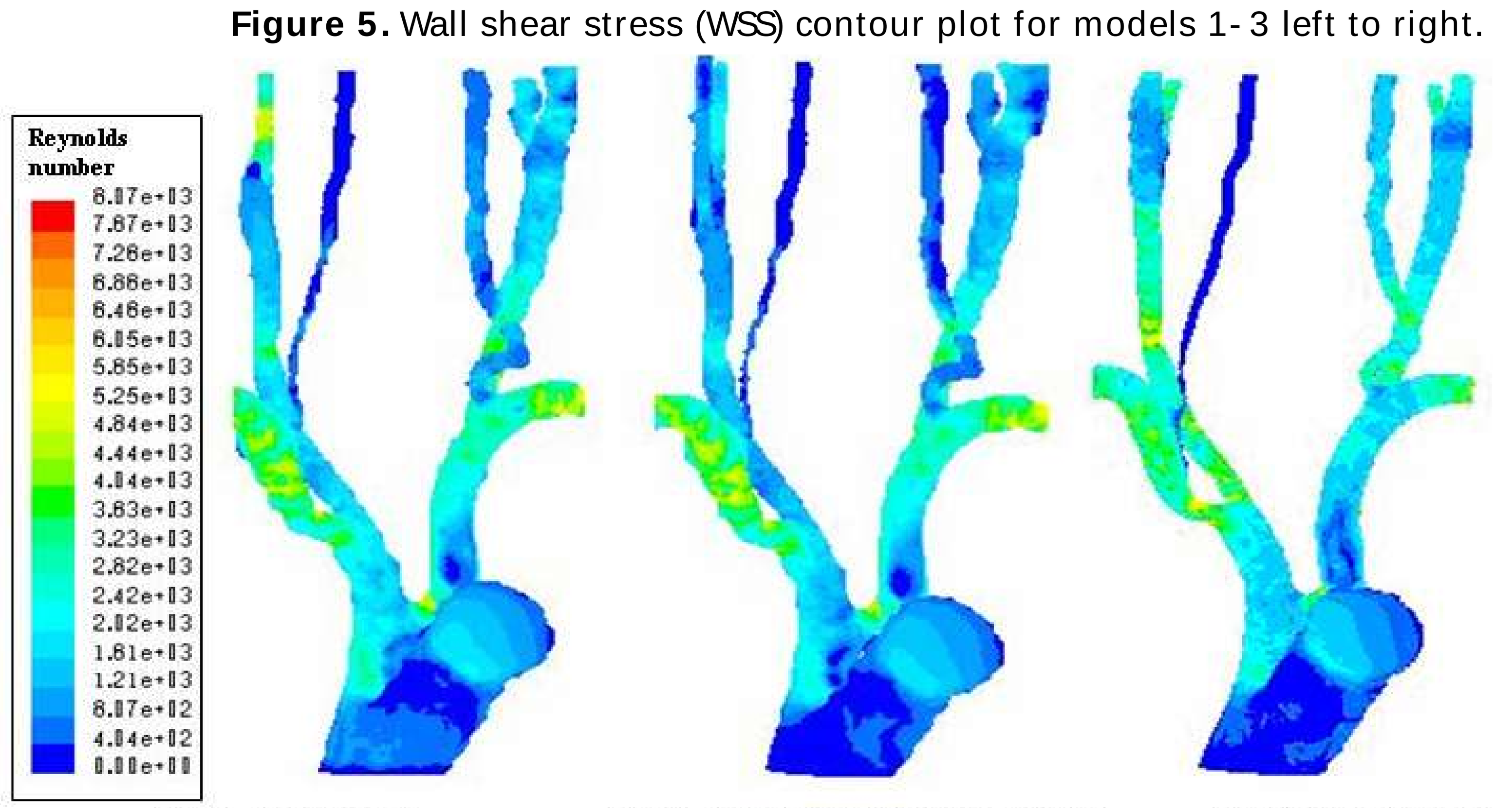

Figure 6. Contour plot of Reynolds number for models 1-3 left to right.

References

[1] Van Tricht Ilse, De Wachter Dirk, Tordior Jan, Verdonck Pascal, 2004. "*Comparison of the hemodynamics in 6mm and 4-7 mm hemodialysis grafts by means of CFD*". Journal of Biomechanics 39 (2006) 226-236

[2] "*The mechanics of the circulation*", C.G. Caro…[et al.]. Oxford University Press, 1978, 527p, Oxford medical publications.

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