Fifth International Conference on CFD in the Process Industries
CSIRO, Melbourne, Australia
13-15 December 2006

3D PATIENT SPECIFIC MODELS OF THE CIRCLE OF WILLIS

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The Circle of Willis *CoW* is a ring-like arterial structure located at the base of the brain and is responsible for the distribution of oxygenated blood throughout the cerebral mass. The circle includes three *communicating* arteries which allow for blood to be rerouted in order to maintain oxygen supply to the cerebral tissue in the event that blood supply through any of the afferent arteries is reduced. Among the general population, approximately 50% have a complete CoW[(1)], where absent or hypoplastic vessels are common, among a multitude of possible anatomical variations, reducing the degree to which blood may be rerouted. While an individual with one of these variations may under normal circumstances suffer no ill effects, there are certain pathological conditions which can present a risk to the person's health and increase the possibility of suffering an ischaemic stroke when compounded with the effects of an anatomical variation.

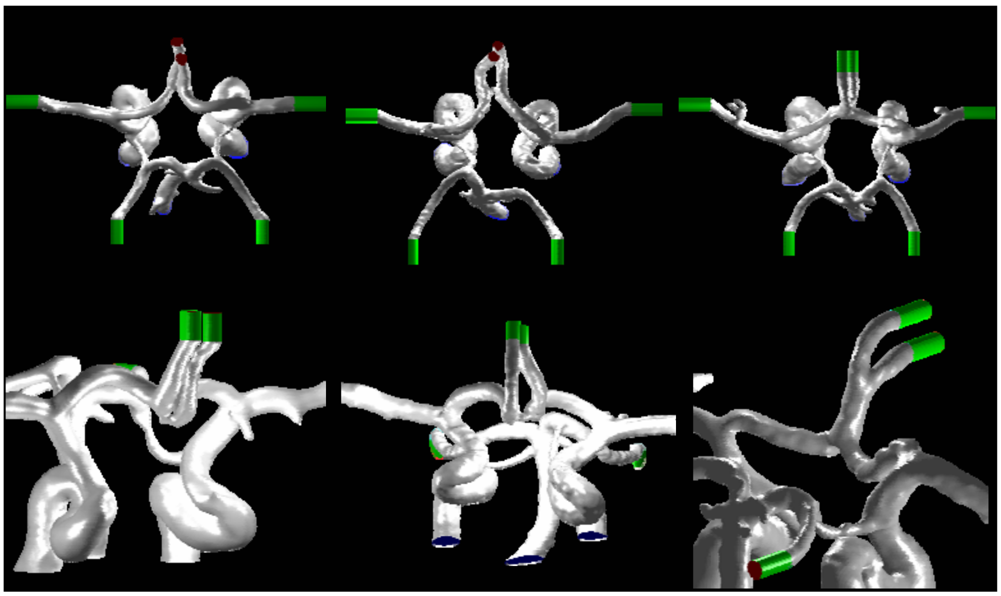

Figure 1. Three anatomical variations of the circle of Willis investigated in the present study a.) a complete CoW b.) a missing right posterior communicating artery and c.) two fused anterior cerebral arteries.

The work presented here however outlines a method using in-house interactive software, incorporating specially developed filtering algorithms and a variation of a standard *marching cube* algorithm, by which patient specific 3D models of the circle of Willis may be rapidly segmented from the MRI *Time of Flight* data. The model uses the novel approach of porous blocks to represent the effects of the distal vascular beds[(2)], which represents a resistance to the flow such that realistic representations of the flow can be achieved. Furthermore, the resistance of the porous block is part of an active control system, representing the body's *autoregulation mechanism,* essentially the body's ability to react to changes in blood pressure in the cerebral territories to maintain homeostasis by altering the diameters of the muscular arteries and arterioles downstream of the CoW. The autoregulation model incorporates some simple blood chemistry, where arterial oxygen and carbon dioxide concentrations can be controlled. It assumes that the driving force for alterations in vascular tone and hence cerebrovascular resistance (*CVR)* is via changes in cerebral tissue levels of carbon dioxide produced as a byproduct of brain metabolism, the removal of which is a function of the cerebral blood flow through the efferent arteries of the CoW. The model also includes the ability of a territory in the brain being perfused by an efferent artery, to regulate its oxygen extraction fraction (*OEF)* based on the amount of blood being perfused, meaning that in cases where cerebral autoregulation might not necessarily be able to restore blood flow to homeostatic levels, more oxygen can be taken from the blood to compensate. The overall result of including these two mechanisms is that oxygen delivery to a territory supplied by the circle of Willis can be predicted in response to occlusions of an artery. In order to calibrate the autoregulation and oxygen extraction dynamic equations, the actual amount of blood flow in the efferent and afferent arteries of a given patient specific CoW model is measured using *CINE Phase Contrast* MRI. The phase contrast scans were performed at the same time as the Time of Flight scan used to create the geometry and were processed with a second piece of in-house, interactive software.

The 3D geometries use an adaptive cartesian meshing technique to create the computational grids, to which the finite volume method was used to solve for the incompressible non-Newtonian blood flow. The modeling methodology was applied to 3 anatomical variations of the circle of Willis found in the study (Figure 1), a complete CoW, a missing posterior communicating artery and two fused anterior cerebral arteries. The simulations performed tested the ability of a given CoW variation to provide collateral flow and hence adequate oxygen delivery to all the territories it supplies following complete occlusions of any one of the three afferent arteries.

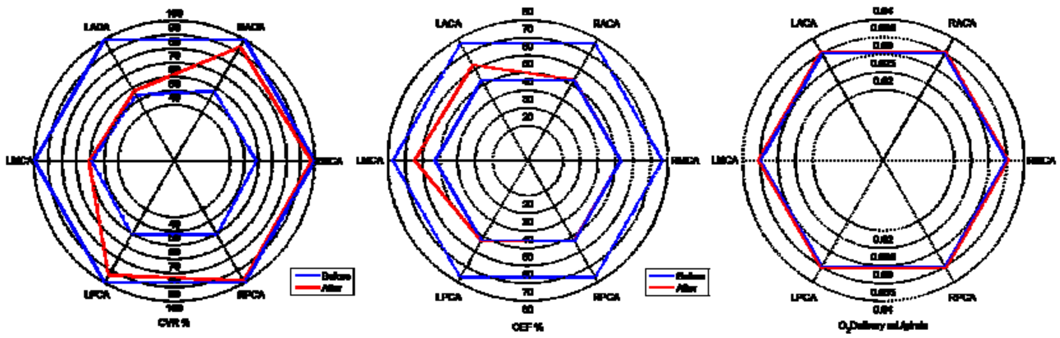

Figure 2. A sample result illustrating the steady state CVR, OEF and Oxygen Delivery to the territories of a brain supplied by a complete circle of Willis following an occlusion of the left internal carotid artery.

A sample result for the complete CoW (Figure 2) illustrates the end response of the six efferent arteries to an occlusion of the left internal carotid artery, in terms of CVR, OEF and oxygen delivery. In this particular case the result shows that the left anterior and middle cerebral arteries are most affected by the occlusion and that the CVR or the territories supplied by these arteries reaches the lower limit of autoregulation (the dashed line in Figure 2), meaning that blood flow will not be completely restored to these territories. As a result OEF increases in these regions, but does not reach its upper limit, meaning that oxygen delivery is able to be maintained to all territories of the brain and ischemic conditions hence avoided. Other simulations include combinations of anatomical CoW variation and occlusion and illustrate cases where oxygen delivery is not always maintained. The results tend to be sensitive to the particular geometry used, highlighting the importance of the use of patient specific models in predicting the outcome of certain cerebral events.

REFERENCES

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