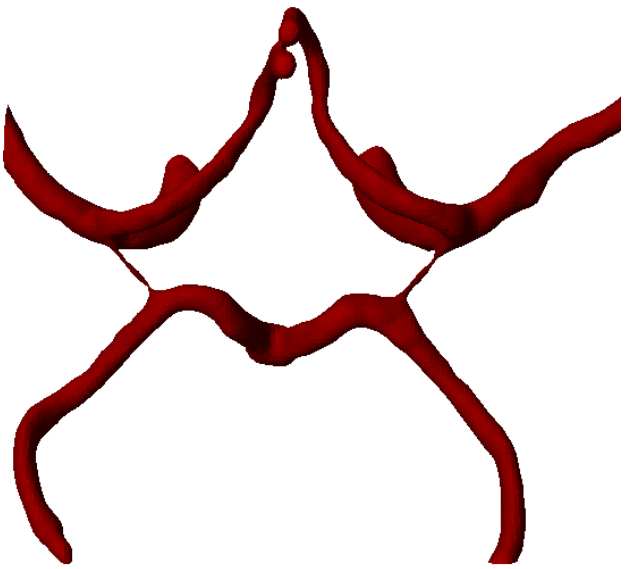
Modelling Blood Flow Through the Circle of Willis:

A Study Combining Image-Based Meshing of MRI Data with CFD



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Introduction

The data from a magnetic resonance imaging (MRI) scan was input into image-based meshing software from Simpleware Ltd, and from this, a finite element (FE) model was created. The model was used to analyse flow through the ring of arteries, known as the circle of Willis, using computational fluid dynamics (CFD) software from ANSYS called ANSYS FLUENT.

The circle of Willis is a ring of arteries in the human brain, which aids in the distribution of oxygenated blood to the tissues of the brain if a main artery on either side becomes partially or fully occluded (blocked).

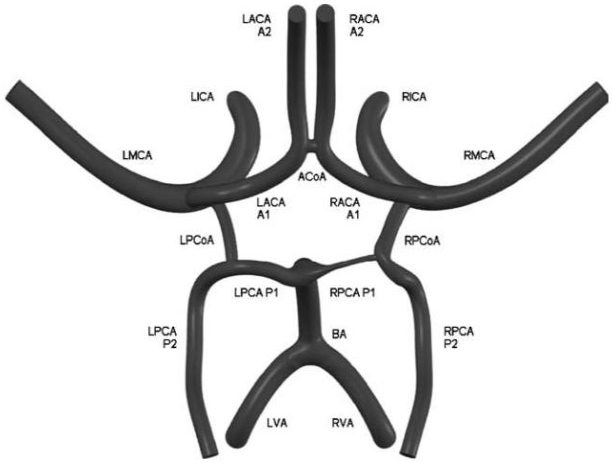


Figure 1: Circle of Willis [1]

A complete circle of Willis is composed of pairs of arteries (left and right), as shown in Figure 1. The vertebral arteries (which join to form the basilar artery (BA) before the circle) and the internal carotid arteries supply the circle with blood. The anterior, middle and posterior cerebral arteries (ACA, MCA and PCA) transport blood away from the circle and these are connected by anterior and posterior communicating arteries (ACoA and PCoA) which allow blood flow to be re-routed if there is reduced in-flow in any of the arteries.

Computational fluid dynamics (CFD) studies have been performed on the circle of Willis, including the use of MRI to resolve the blood flow through the arteries. The technique of using time-resolved MRI data to show blood flow has been extensively used in various vessels, covered in later sections. A study by Long *et al.* [2] used MRI to define the geometry of the circle of Willis, though the results were simplified to give a generic geometry for analysis. This study used MRI data with image-based meshing software to create a FE model of the circle of Willis, with geometry accurate to one individual.

The aim for this research was to pave the way for the technique to be used as a clinical tool, and suggest that in future, patient-specific circle of Willis models could be segmented directly from MRI data of an individual's cerebral vasculature, to allow patient-specific treatment based on accurate modelling.

Background

This section looks at:

1. FE modelling with ScanIP and ScanFE,
2. Modelling blood flow, and
3. Previous modelling of the circle of Willis.

FE Modelling with ScanIP and ScanFE

ScanIP and ScanFE were created by a company called Simpleware based in Exeter.

ScanIP is an image processing program which can work with 2D or 3D data sets. Images can be imported in different file formats including very importantly, DICOM (Digital Imaging and Communications in Medicine) data, which include sources such as MRI and Computed Tomography (CT) scans, both of which are continuous monochromatic representations of the scanned object. The software can import a large range of image formats, so there is little chance of an image being in an unsupported format.

Once an image/s is imported, it can be processed using a large number of functions, and the user can manipulate the data to get the required output. The output from ScanIP is a segmented set of masks which can be used in place of the background image. The benefit of masking the data is that it becomes a simple binary representation of the pixels which fit the criteria specified by the user when defining the mask.

The area to be masked can be defined by the greyscale value of the pixels (e.g. masking all pixels with a value greater than 200) or it can be painted on manually (only two options of many). The data itself can be filtered and smoothed using a large number of filters, or, once applied, the same operations (and more) can be applied to the masks. An exported model can contain very few masks, or a very large number, depending on the requirements for the next stage of processing. Once complete, the model can be exported to ScanFE for meshing (though the surface can be exported to a wider range of programs).

ScanFE is a finite element program which imports the masks produced in ScanIP and allows the user to mesh them in a limited number of ways. ScanFE is very simple to use and produces a mesh which can be exported into a range of different FEA packages.

The use of these programs in this study will be covered in the methodology section.

Modelling Blood Flow

There has been a large amount of research into flow through blood vessels. This has involved mainly computational and physical modelling though there have also been some experimental studies.[3]

Blood is a non-homogeneous, non-Newtonian fluid which flows through veins and arteries which have non-linear elastic properties. Petkova *et al.* [4] incorporated an estimated non-Newtonian property in some of their models and found only slight differences between the results for Newtonian and non-Newtonian models around the blockages, suggesting that a Newtonian approximation is acceptable for similar cases. The shear-thinning non-Newtonian effect can be added into a CFD model using the Carreau-Yasuda viscosity model found in a paper by Gijsen *et al.* [5]. In Fluent, non-Newtonian viscosity is specified through a User Defined Function.

A study by Marshall *et al.* [6] made use of MRI to collect time-resolved velocity measurements of the blood flowing through the carotid artery bifurcation (they did not collect geometrical data). They used the information gathered to apply boundary conditions to a CFD model of the region. The computations used by Marshall *et al.* were third-order quadratic differencing scheme (QUICK) for spacial differencing and fully implicit backward Euler differencing for time.

Blood flow is pulsatile, not steady, and some work, including the Marshall *et al.* study, have included this in their models. Pulsing flow requires cyclic measurements to ensure all phases of the pulse are analysed.

Another study which used time-resolved flow data was by Leuprecht *et al.*[7] The Newtonian blood model in this study used a density of ρ=1044kg/m^3 and a constant viscosity of μ=3.65x10^{-3} Pa s. The Reynolds number for the flow was approximately 948.

A CFD/FEA study performed by Tittelbaugh *et al.*[8] used pulsatile flow with a frequency of 1.2Hz (simulating 72 heartbeats per minute, bpm), and a pressure fluctuating around a mean of 100mmHg. All blood vessel models in this study were axisymmetric, focusing on coupling the FEA and CFD results rather than complexity.

The above papers all deal with various aspects of the computational modelling of blood flow in various parts of the body. There are numerous approaches to the modelling of such a complex system; some assume steady-state, incompressible, non-Newtonian flow, and others introduce pulsatile or non-Newtonian flow. Some of the reports contain information very useful in setting up a similar case; domain information and many constants used for the models have been published, allowing an approximate model to be set up using this data before being adjusted for the specific case. It also shows that it is not frowned upon to make the larger assumptions associated with the modelling of blood flow, otherwise, the complexity of cases would be too great.

Previous Modelling of the Circle of Willis

The circle of Willis is named after the first man to detect it and suggest part of its purpose – Thomas Willis.

According to Symonds [9], in 1684 in his published book, Willis said of the arteries and the circle:

> *"that there may be a manifold way ... for the blood to go into divers Regions of the Brain, ... so that if by chance one or two should be stopt, there might easily be found another passage instead of them: as for example, if the Carotid of one side should be obstructed, then the Vessels of the other side might provide for either Province." [9]*

This function of the circle has been backed up by research in the centuries since, and it is commonly accepted as a major function of the anatomy. Human Anatomy and Physiology Textbook [10] summarises the circle of Willis as:

> *"[The circle of Willis] unites the brain's anterior and posterior blood supplies. It also acts to equalise blood pressure in the two brain areas and provides alternative routes for blood to reach the brain tissue if a carotid or vertebral artery becomes occluded." [10]*

Cieslicki and Ciesla [11] state that the pressure-flow relations are non-linear in all sections of the circle of Willis, and to enable the calculation of the non-linear resistance of the arteries, earlier study by Cieslicki *et al.* [12, 13] developed two formulae to be used in the computational study of the circle of Willis region.

In what they claim is the first 3D flow study on the circle of Willis to look at the effect of stenoses, Long *et al.* [2] used MRI data to create a 3D model using SOLIDWORKS, though they simplify the geometry to make a very generic model – the MRI data is used to approximate the shapes. One of their cases has an incomplete circle of Willis – based on information from Alpers *et al.* [14] which says that only around 50% of the general population have a complete circle. Long *et al.* show that a 51% blockage does not have much effect on the pressure distribution around the circle of Willis, but an 86% or 96% blockage causes a significant pressure difference. The discussion of the paper contains a fairly strong disclaimer on the techniques used:

> *"Validation of this kind of CFD study has proven to be difficult. Firstly, the study is designed to prove a concept under assumptions which may not be true in reality such as constant outflow rates ... Secondly, the accurate measurement of blood flow rate and pressure in the small collateral vessels is almost impossible. Therefore, the comparisons of the simulation results to published data are limited to the larger vessels, and are currently not available for the communicating arteries." [14]*

This does not mean that the research is not useful – it just means that currently it is very difficult to truly validate the results, but that the method is a powerful way of proving concepts for future work.

The most thorough and realistic modelling found of the Circle of Willis, and indeed blood flow in general, was that of Moore, S. *et al.* [1] in 2006. The group made use of MRI to get a few points along the arteries, and generated generic models using CAD software. They modelled three different conditions (one normal, one missing an artery and the other having a much-reduced arterial diameter), and added more of the true parameters of blood than any other study shown. The research made use of a lot of the ground work performed by others and drew many years of work together to get results for an unsteady, non-Newtonian viscous flow through the complex network of arteries. The effect of truncating the arteries close to the circle was discussed, and it was decided to model a porous block at the end of the out-flowing arteries to introduce the resistance equivalent to blood flowing into the rest of the vascular network. The porous block model was developed by Ferrandez *et al.* [15] and David *et al.* [16]; both 2D modelling studies of the circle of Willis. The Moore, S. *et al.* paper identified the need to define the positive and negative direction of flow in each artery in order to document the flow rates.

Moore, S. *et al.* showed that the internal carotid artery supplies around three times as much blood as the vertebral arteries. In a healthy, normal circle of Willis, there is essentially zero flow through the anterior communicating artery, and a small, equal amount flowing through the posterior communicating arteries. Due to the complexity of the model, validation is a major issue. MRI time-resolved data has been used in other studies, but as far as Moore, S. *et al.* could ascertain, it has not been used to quantitatively measure the flow for the communicating arteries.

Methodology

Many stages were required to get to the point where a model could be input into a CFD package. Initially, the data was imported into ScanIP using the 'DICOM images' importing function. On the disc provided by J. Fulford, were the images from a number of different scans, and each of these were looked at to find the one with the best contrast for the blood vessels of interest.

Once the image stack had been chosen, the region containing the circle of Willis was identified, and then the data cropped before importing, to cut off the unwanted regions, such as the neck and extremities of the brain.

Once in ScanIP, a mask was applied to the data, covering pixels with a greyscale value 80 – 255 (mid grey to white). This produced the 3D image shown in Figure 2, below. The first thing that stands out is the absence of the anterior and posterior communicating arteries (ACoA and PCoA) which complete the circle of Willis.

Figure 2: Initial Data Segmentation

Before looking in detail at the absence of the circle of Willis, the presence of unwanted artefacts was addressed.

Two simple methods were used to reduce the amount of extra masked data. Firstly, the area of interest was far smaller than that initially masked, so the domain was reduced by cropping the data to exclude the thinner vessels at the edges of Figure 1. Secondly, the remaining unwanted pixels of the mask were "unpainted" using the facility in ScanIP.

The resulting, cleaned up mask is shown in Figure 3, and is labelled to show the abbreviation for each artery which transports blood away from the circle.

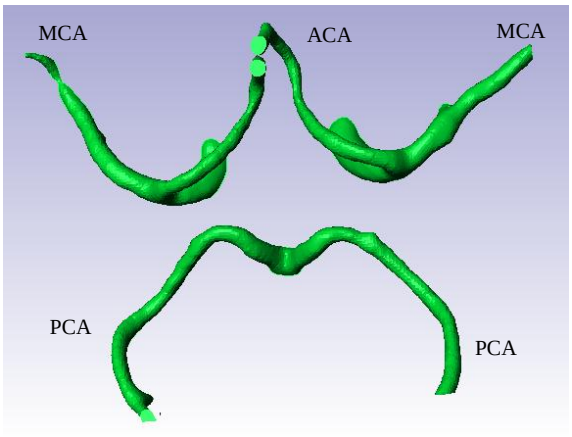


Figure 3: Outflowing Arteries

The anterior, middle and posterior cerebral arteries (ACA, MCA and PCA) showed up very clearly on the MRI scan, but, the smaller ACoA and PCoA were not detected by the MRI scan.

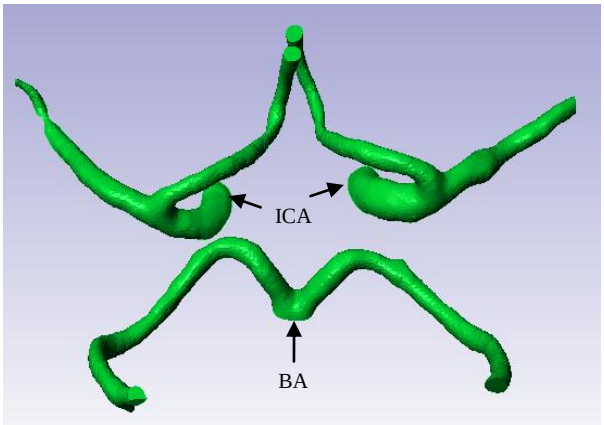


Figure 4: Inflowing Arteries

Figure 4 shows the arteries flowing into the circle of Willis. The vertebral arteries which are present in Figure 1 are outside of the modelled domain, leaving just the basilar artery (BA) and the internal carotid arteries (ICA) in the model.

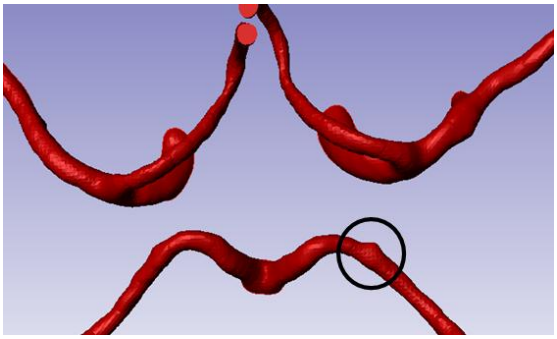


Figure 5: Location of PCoA

There is evidence to support the presence of the circle of Willis in the patient; Figure 5 shows the 3D image at a different angle and highlights the connection between one of the PCoAs and the PCA.

The discovery of this bulge in the PCA lead the author to go back to the MRI data and experiment with different thresholds to investigate how much of the PCoA could be modelled in this way.

A new mask with a wider threshold extended the range of the PCoA, but it also introduced many false artefacts, as much of the tissue of the brain had the same greyscale value as the region of the smaller arteries. Instead, the author had to use the paint function in ScanIP to locate individual pixels which may belong to the PCoAs and add them to the mask, to build up a 3D image of the path of the arteries which did not show up at first.

It was very difficult to track the progression of the small arteries, and in fact, it was not possible to complete the artery between the anterior and posterior cerebral arteries.

The progress made using this method is shown in Figure 6.

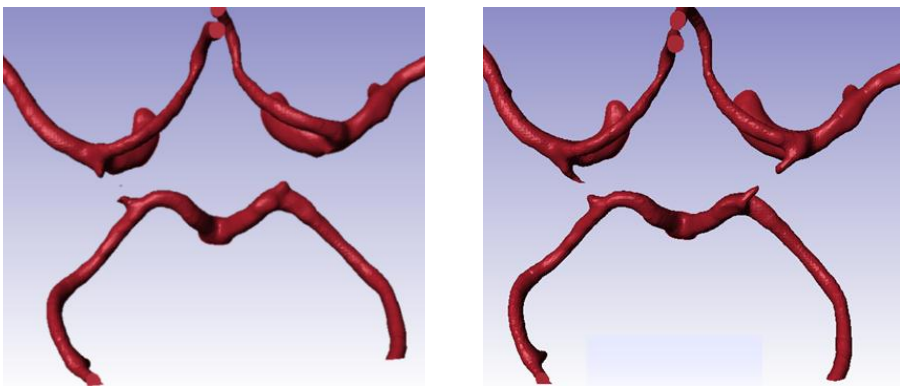


Figure 6: Models showing pixel-painted PCoA

Due to the lack of pixels showing the PCoAs and ACoA in the MRI data, it was necessary to use a different approach to solve the problem. Simpleware Ltd. also produce a program called ScanCAD, which can be used to join CAD files to image-based meshes. This ability is particularly important in the medical profession, and is used in the design and FEA of such parts as hip replacements, where the bone is modelled from DICOM data, and the replacement hip is modelled in CAD software.

In this instance, ScanCAD was used to create artificial geometry for the ACoA and PCoAs, to merge with the MRI-based mesh of the rest of the arteries.

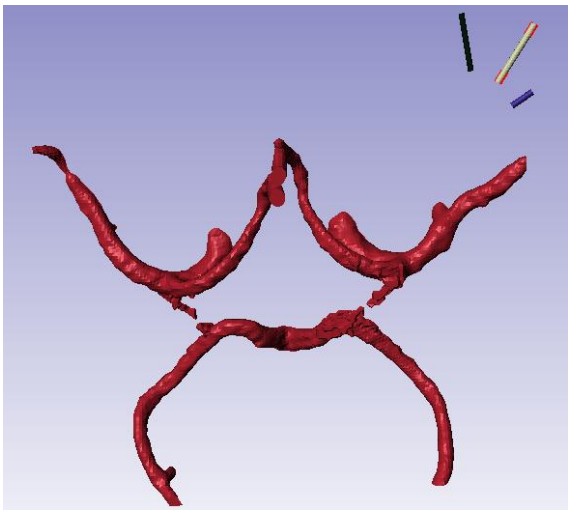


Figure 7: Mask in ScanCAD with Artificial PCoAs and ACoA

Simple cylinders were used to mimic the circle of Willis arteries. The ACoA was given a diameter of 0.8mm, and the PCoAs of 1mm, based on the scale of the rest of the arteries and the values used in other similar studies.

The cylinders were created in ScanCAD, which has the facility to create very simple geometries.

The model with the pixel-painted PCoAs was used as a basis for the first model.

The CAD parts were manoeuvred into position using "widgets" in the programme which control the translation and rotation of individual parts.

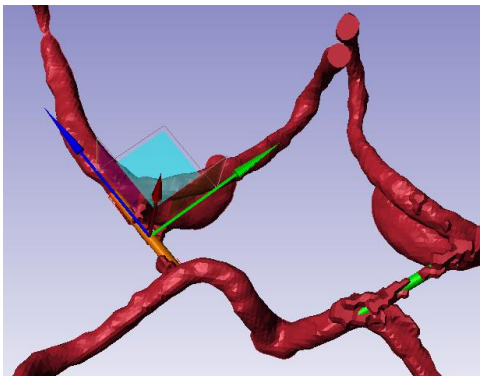


Figure 8: Translation Widget in ScanCAD

Figure 8 shows the translation widget being used to position the left PCoA.

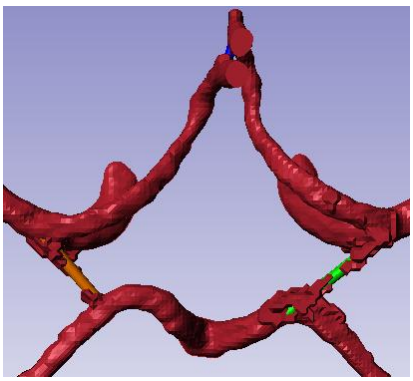


Figure 9: Complete Circle of Willis with Pixel-Painted Mask

Once the three communicating arteries were in position, it was clear that the pixel-painted sections of the PCoAs were not adding any benefit to the model.

An earlier version of the model was imported into ScanCAD to use with the same artificial arteries, Figure 10 shows the set-up of the model and the comparative simplicity of the simpler design.

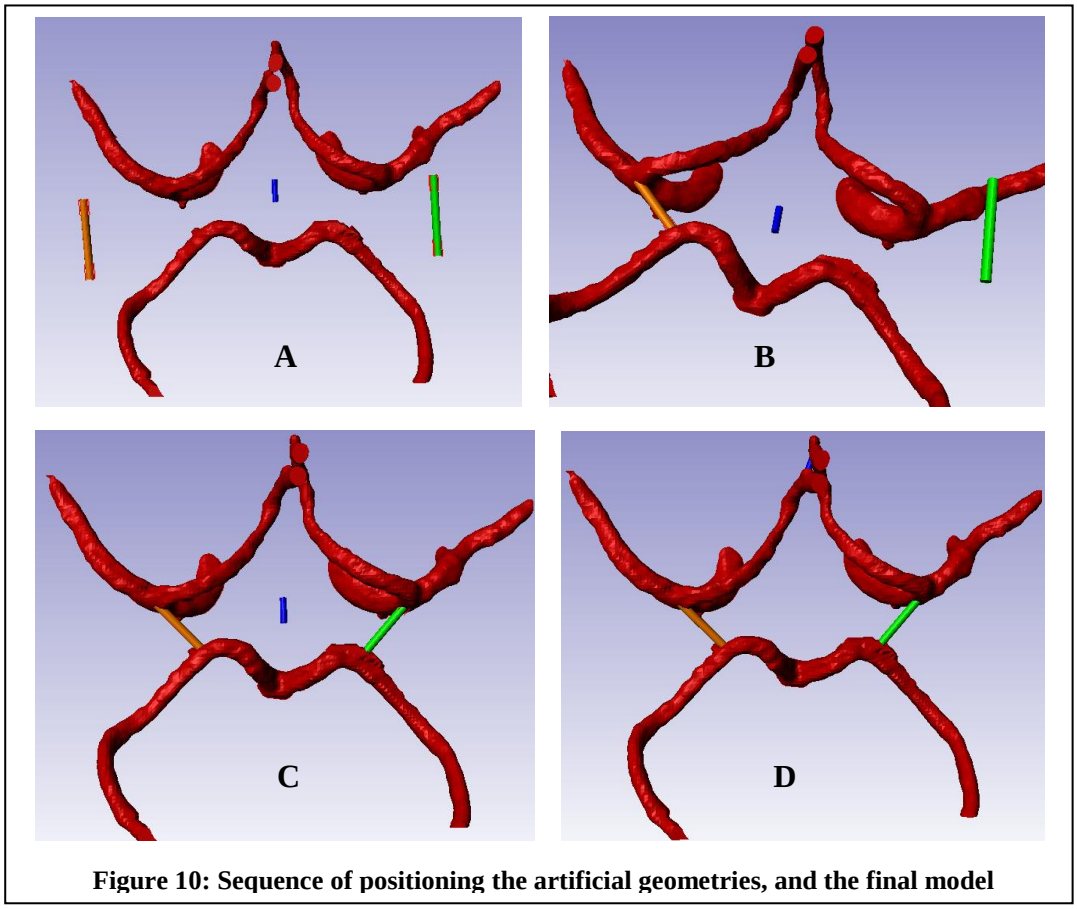
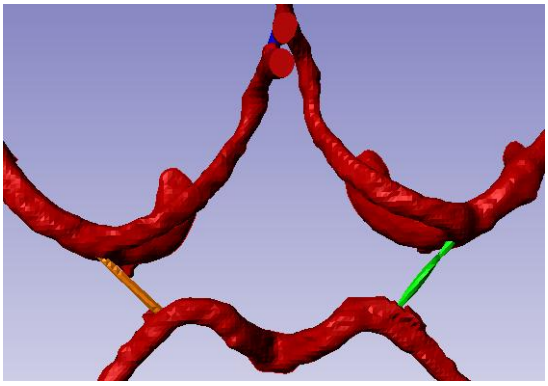


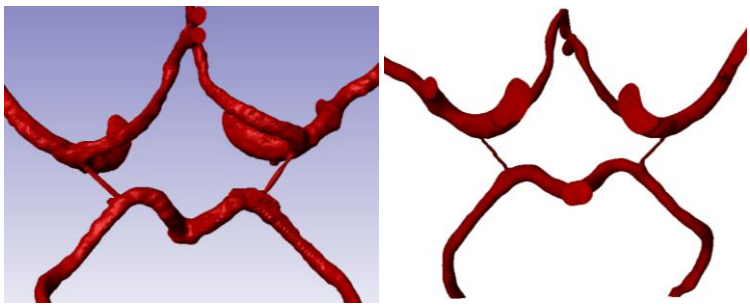
Figure 10: Sequence of positioning the artificial geometries, and the final model

Once all the parts were positioned in ScanCAD, the CAD parts were converted to masks, and then the four masks were exported to ScanIP.



Once converted to masks, the CAD parts lost their precise dimensions, and were distorted as they were voxelised. In ScanIP, the communicating arteries had similar surface defects to the other arteries.

Figure 11: Circle of Willis, 4 masks in ScanIP



The four masks were added together to create a single mask using the Boolean Union function in ScanIP, and then exported to ScanFE, where it was meshed (Figure 12).

Figure 12: Full model in ScanIP (left) and ScanFE (right)

Before exporting the model for use in a CFD package, the boundary conditions had to be defined. The complex, asymmetric nature of the network meant that the left and right branches of the MCA were not flowing out of faces opposite each other. To reduce the complexity, and make the model more symmetric, the domain was reduced by 5 pixels at the minimum end of the x-axis (XMIN in ScanIP).

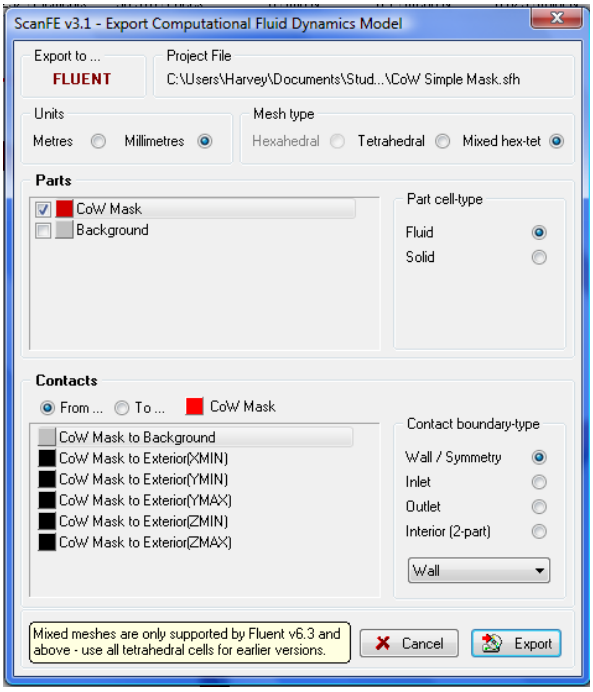


Figure 13: Export to Fluent Menu

Exporting the first full model of the circle of Willis was not successful. Figure 13 shows the range of options for each boundary (minimum and maximum of the domain at each axis).

After exploring many different options, it was found that exporting a single model from ScanFE using the wizard shown in Figure 13 was the only way to create a model with any boundary conditions in Fluent, though it did not allow boundary conditions to be added to individual inlets and outlets, only flow through all inlets or outlets on one face of the volume.

Methods attempted included exporting ACIS (*.sat) and IGES (*.igs) files from ScanIP which contain the node data, but these could not be made into a single volume in SolidWorks or meshed in Gambit.

Results

Once imported into Fluent, it was necessary to separate out the different inlets and outlets, as it is not currently possible to do this in ScanIP or ScanFE.[17] Where more than one blood vessel is in contact with one face of the cuboids volume, it is necessary to split them up into separate faces, as Simpleware does not currently allow them to be defined separately. This is done in Fluent, by using the "Separate regions" function.

Grid → Separate → Faces → Region → select which face of the volume to separate

The region will then be split into as many distinct regions as there are vessels touching that region. This function helped to identify where the model was not perfectly contained within the volume – some of the blood vessels were in contact with both ZMAX and either XMIN or XMAX. This discovery led to the removal of some mask pixels and the addition of padding to the model to ensure that the mask should not touch the edge of the volume unless there should be flow through that surface.

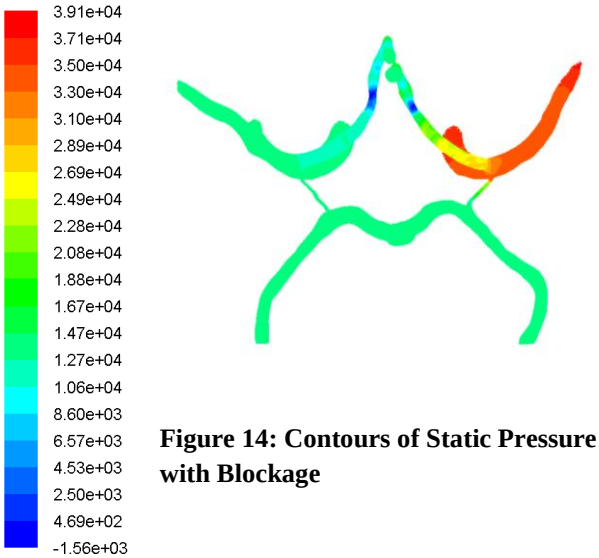


Figure 14: Contours of Static Pressure with Blockage

Figure 14 shows the high pressure which resulted when one of the outlets was not in contact with the edge of the volume.

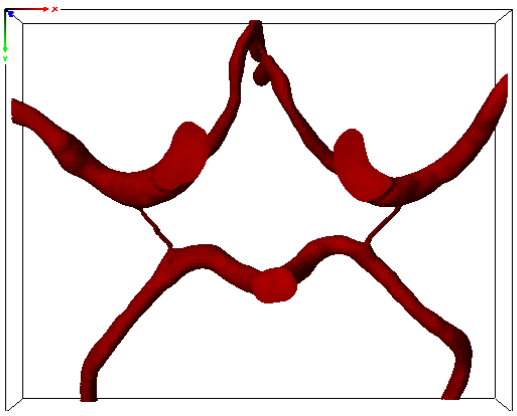


Figure 15: Final Circle of Willis Model

Figure 15 shows the final model which was used in Fluent, with all inlets and outlets touching the appropriate surface of the volume, and the spacer pixels in place to ensure no extra regions are generated in Fluent.

The parameters used in the simulation were based on those used in the literature survey.

Pressure inlets = 100mm/Hg = 13332 Pa

Velocity = 0.25m/s

Density = 1044kg/m^3

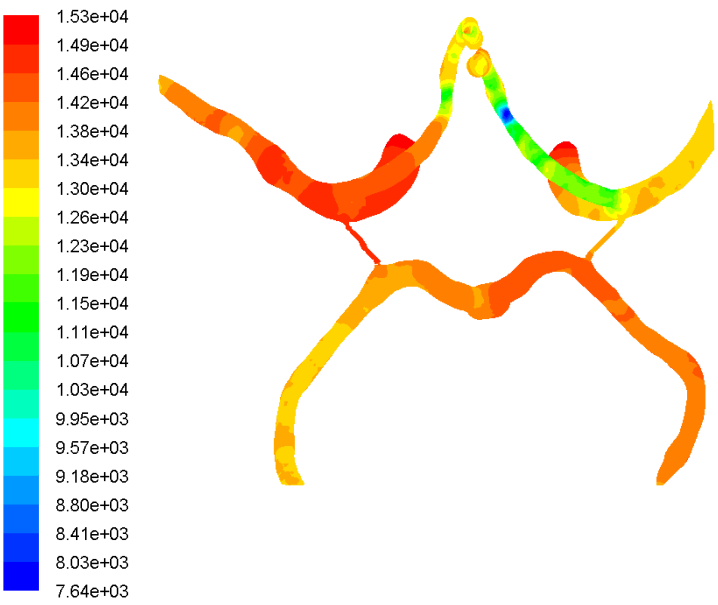


Figure 16: Pressure Contours(Pa) for Final Model

Viscosity = $3.65x10^{-3}$ Pas = $3.65x10^{-3}$

After 1211 iterations, the solution converged; Figure 16 shows the pressure contours for the model. The pressure contours show a significant pressure drop around a region of thinning in the ACA.

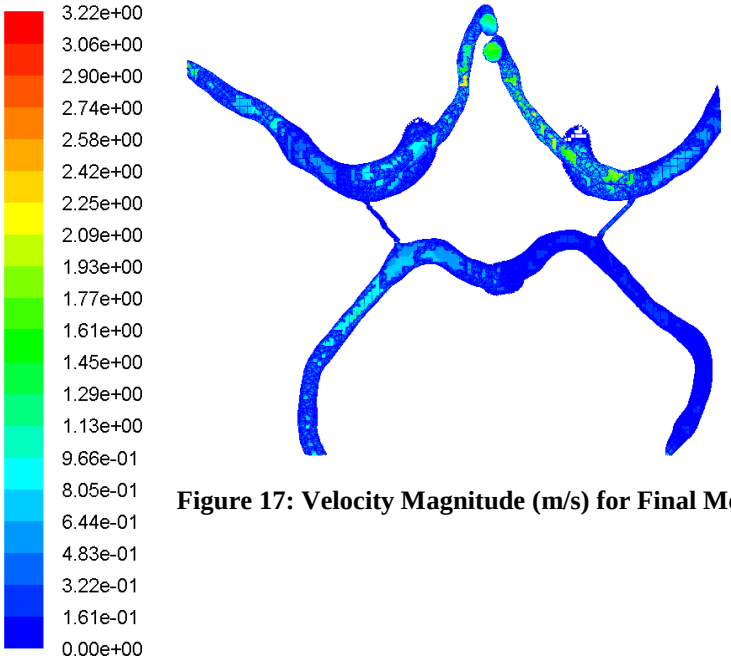


Figure 17: Velocity Magnitude (m/s) for Final Model

Figure 17 shows the Velocity magnitude for the same study, where there is no hint of a velocity increase to explain the decrease in pressure.

In order to identify whether or not the pressure drop is a true effect, or whether it is just an error introduced into the computational model, a mesh refinement study should be performed to see if the effect remains with a finer mesh.

Mesh refinement would generally be the next step in any study like this to establish the cost-benefit of using a particular number of elements in a model – the trade-off is between accuracy and time/computing power available. Mesh refinement in Simpleware is primitive, allowing the user to place mesh morphing spheres at certain locations to increase the mesh density around a point of interest. This requires the data to be resampled in a cubic fashion, which, in this case, decreased the accuracy of the model and added in areas around the model which stopped the model touching the edge of the volume.

Conclusion

The initial aim of creating a geometrically accurate model of an individual's circle of Willis was not met, however, the method of creating a model and applying the boundary conditions has been explored. The results of the initial studies in Fluent show that the model is workable, and that can be used to simulate the blood flow through the circle of Willis.

The absence of a clear circle of Willis in the data was a hindrance to progress – as the initial aim was to create the entire model using segmented MRI data. The addition of the CAD parts to the model was not ideal, but allowed the model to be imported into Fluent with all parts interacting.

In a future study, it is recommended that the user exports the data from ScanIP without using the mesh refinement tools, and instead finds an intermediary programme which allows tight control over the mesh density and the inlet/outlet properties. This can then be used to export to Fluent and run the mesh refinement study, before embarking on a full study devoted to modelling the flow around the circle of Willis.

Further MRI scans of the circle of Willis could be analysed, as it may be an anomaly in the data or the patient which led to the lack of the fine arteries in the modelling. A larger number of scans would also lend itself to the possibility of comparing different geometries as there is clearly a high degree of asymmetry to determine differences in flow due to the varying orientations, degrees of bend and asymmetry in artery thickness on the flow around the circle of Willis

This report and accompanying data could be used as a basis for future work, allowing the research to focus on the larger scope of the project, limiting the time spent on setting up and segmenting the data, researching appropriate boundary conditions and applying them to models.

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References

[1] **Moore, S., David, T., Chasea, J.G, Arnolda, J., Fink, J**. (2006). *3D models of blood flow in the cerebral vasculature*. Journal of Biomechanics 39, pp. 1454-63

[2] **Long, Q., Luppi, L., König, C.S., Rinaldo, V., Das, S.K.** (2008). *Study of the collateral capacity of the Circle of Willis of patients with severe carotid artery stenosis by 3D computational modelling*. Journal of Biomechanics 41, pp. 2735-42

[3] **Reul, H**. (1984). *Cardiovascular simulation models*. Life support Systems 24, pp. 77-98

[4] **Petkova, S., Hossain, A., Naser, J., Palombo, E**. (2003). *CFD modelling of blood flow in Portal vein hypertension with and without thrombosis*, Proc 3rd International Conference on CFD in the Minerals and Process Industries, Melbourne, 10/12/2003, pp. 527-530

[5] **Gijsen, F., Van de Vosse, F., Janssen, J**. (1999). *The influence of the non-Newtonian properties of blood on the flow in large arteries: steady flow in a carotid bifurcation model*. Journal of Biomechanics 32, pp. 601-608

[6] **Marshall, I., Zhao, S., Papathanasopoulou, P., Hoskins, P., Xu, X.Y**. (2004). *MRI and CFD studies of pulsatile flow in healthy and stenosed carotid bifurcation models*. Journal of Biomechanics 37, pp. 679-687

[7] **Leuprecht, A., Kozerke, S., Boesiger, P., Perktold, K**. (2003). *Blood flow in the human ascending aorta: a combined MRI and CFD study*. Journal of Engineering Mathematics 47, pp. 387-404

[8] **Tittlebaugh, E.M., Fu, R., Sett, S**. (2007). *Coupling FEA to CFD to investigate the effects of pulsatile blood flow on the dilatation of artery walls* [online]. Available: www.ensight.com/images/stories/pdf/NWC07- tittelbaugh-fu-sett_abaqus_fluent_fsi_nafems_2007_paper.pdf [accessed Feb 2010]

[9] **Symonds, C**. (1955). *The Circle of Willis*. The British Medical Journal 1, pp. 119-124

[10] **Marieb, E**. (2001). Human Anatomy and Physiology, 5th ed., USA, Benjamin Cummings, pp. 755

[11] **Cieslicki, K., Ciesla, D.** (2005). *Investigations of flow and pressure distributions in physical model of the circle of Willis.* Journal of Biomechanics 38, pp. 2302-10

[12] **Cieslicki, K., Lasowska, A., Smolarski, A.Z**. (2000). *Influence of channel tortuousity on hydraulic resistance*. Bulletin of the Polish Academy of Science series: Earth Science 48, pp. 161-73

[13] **Cieslicki, K., Lasowska, A., Smolarski, A.Z**. (2000). *Pressure-flow relation of arterial segments of variable geometry*. Polish Journal of Medical Physics and Engineering 6, pp. 55-67

[14] **Alpers, B.J., Berry, R.G., Paddison, R.M**. (1959). *Anatomical studies of the circle of Willis in normal brain*. AMA Archives of Neurology and Psychiatry 81, pp. 409-18

[15] **Ferrandez, A., David, T., Brown, M.D**. (2002). *Numerical models of auto-regulation and blood flow in the cerebral circulation*. Computational Methods in Biomechanics and Biomedical Engineering Volume 5, pp. 7-19

[16] **David, T., Brown, M., Ferrandez, A**. (2003). Auto-*regulation and blood flow in the cerebral circulation*. International Journal for Numerical Methods in Fluids Volume 43, pp. 701-13

[17] **Bui Xuan, V**. Simpleware Ltd. *Circle of Willis.* Personal Email 6 May 2010.