Modelling Blood Flow in Coronary Arteries with Junctions

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Abstract

Numerical modelling of the coronary tree is well established. Solutions of the Navier-Stokes equations can produce wall shear stress distributions which can be used to correlate the position of shear stress distribution with coronary artery disease.

We have previously demonstrated a technique for reconstructing a single branch of the coronary tree. The introduction of junctions into the model allows for accurate reconstruction of potentially the entire arterial tree. However the introduction of a realistic junction has proven to be difficult.

A four section method for branching has been adopted, utilising three tubular segments and a small junction section as the join. This allows for automatic generation of the majority of the artery (the tubes), and a semi-automated procedure concentrating specifically on the junction. A structured mesh is used for the tubes, allowing for easy generation and improved computation time, whilst an unstructured mesh is used to accurately model the irregular shape of the junction.

The four section method allows for easy insertion of more branches, depending on the level of detail required. Another advantage is that as time evolves, inducing conformational changes throughout the cardiac cycle, the tubes can be regenerated, whilst the junction needs only slight modification.

Marked changes are induced in wall shear stress by either adding extra junctions to an arterial tree, or altering the shape of major branches.

1. Introduction

Atheroma in human coronary arteries has a predilection for certain sites. Of the factors which are thought to contribute to atheroma formation, the patterns of flow and the structure of the wall are the only two which might relate to the position of atheroma. The wall shear stress is governed by the conditions of blood flow at the arterial wall, with regions of low shear stress believed to favour atheroma formation. Asakura and Karino [1] have measured flows in a reconstructed coronary artery by fixing the artery tree to a frame, rendering the walls transparent and observing particle paths. This work showed remodelling to be a function of flow. Observations from the pathologic study of young persons dying of accidents have shown a predilection of atheroma in coronary arteries to be in certain sites [2].

2. Methods

This study was approved by the University of Tasmania and the Royal Hobart Hospital Human ethics committee.

A technique for reconstructing a single branch of the coronary tree has previously been shown [3, 4]. The introduction of branches into the model allows for accurate reconstruction of potentially the entire arterial tree. However the introduction of a realistic junction has proven to be a non-trivial task.

Biplane angiograms are used to determine a pointwise reconstruction of the centreline of the artery in three dimensions, using an adaptation of the technique developed by Metz and Fencil [5], as well as two radii at each point. This information is now used to create a mesh suitable for computational fluid dynamical modelling of blood flow in the artery. The first step in constructing this mesh is to separate the artery into junctions and the non-branched sections between junctions, henceforth known as tubes.

For simplicity a single junction and surrounding tubes shall be considered.

The three tubes are meshed separately and then combined with the junction in order to carry out fluid dynamics simulations. The tubes are generated automatically, the process can be outlined as follows [4]: the first step is to interpolate the centreline up to about 400 points using a cubic spline, so that a smooth artery is achieved. The radii are also interpolated, but in this case linear interpolation is used due to the localised changes in radius along the artery. Next, a mesh is constructed for a unit circle in the x-y plane centred at the origin. This mesh is then re-oriented so that it lies in the entrance plane of the tube, before being extruded along the centreline, changing the radii as necessary.

The junction is created in a semi-automatic fashion using the software package CFD-GEOM^{TM}. CFD-GEOM is an interactive mesh generation application developed as part of a suite of computational fluid dynamics packages by

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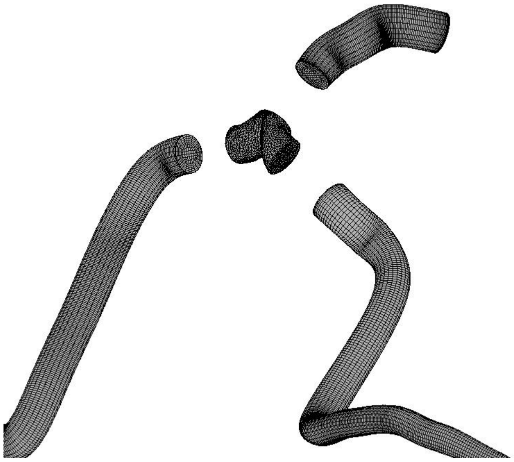

Figure 1. An exploded view of a branched artery. Note the combination of structured and unstructured meshes.

CFD Research Corporation (Huntsville, Alabama). In order to faithfully mesh a junction it is necessary to include in the mesh file the three points immediately surrounding the junction and the fiducial point which marks the actual junction. The entrance/exit planes of the junction must be defined so that they coincide with the exit/entrance planes of the tubes. The surface of the junction is created by intersecting the two cubic spline interpolated mini tubes made up of the ellipses surrounding the entrance point, fiducial point and one of the exit points. Once defined, a mesh can be patched on to the surface, and then a finite element mesh is generated automatically using the CFD-GEOM package. The result is an unstructured mesh, with elements in a chosen volume range.

The three tubes and junction are joined together using the CFD-GEOM package. It is vital that the junction and tubes do not overlap, however a small air gap is allowed which is filled in automatically. A second important consideration is matching the continuity of the gradient of the surface of the artery at the joins. This problem can be overcome by ensuring the location of the join is in a region where the radius of the artery is not rapidly changing, and the artery is not undergoing significant bending. Figure 1 shows an exploded view of a branched artery.

The advantages and issues arising out of the 4 part method as outlined have been discussed elsewhere [4] and shall not be repeated.

3. Results

3.1. Effect of differing junctions on wall shear stress

The introduction of a branch into an artery can induce marked changes in the wall shear stress in the region of the branch. Figure 2 shows the right coronary artery with the branches removed, and a close up of the corner section where a bifurcation should be. The boundary conditions for the artery are an input velocity of $0.2ms^{-1}$ and an output pressure of $0Nm^{-2}$. The three images in figure 3 show the same artery with the same boundary conditions. In each image the branch has been constructed using a slightly different method.

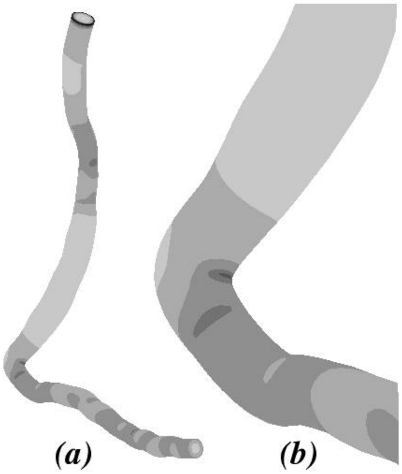

Figure 2. Wall shear stress in a right coronary artery with the branches removed. (a) A major section of the artery. (b) A close up of the corner region where one of the removed branches should be. The wall shear stress ranges from $0Nm^{-2}$ (white) to $9Nm^{-2}$ (black).

First consider the branched arteries as a group, and how they compare to the non-branched version. The wall shear stress in the region surrounding the branch is significantly more complicated in the branched arteries compared to the non-branched artery. The maximum stress is higher, as is the spatial variation on the inner wall and below the junction. This illustrates the importance of including branches in any model of wall shear stress in coronary arteries.

Now consider the differences in the three images in figure 3. Figure 3a was generated using an unstructured mesh for the entire artery (*i.e.* not using the 4 part method), whilst 3b and 3c were generated using the 4 part method, but with different patches used to construct the surface of the junction.

The arteries in figures 3a and 3b display similar wall shear stress, both in magnitude and extent of variation. This suggests that the 4 part method developed can be used to accurately model wall shear stress in the regions of junctions, however the 4 part method has advantages over a mesh made of only unstructured elements, these are outlined below.

- The tube sections are generated automatically, and thus

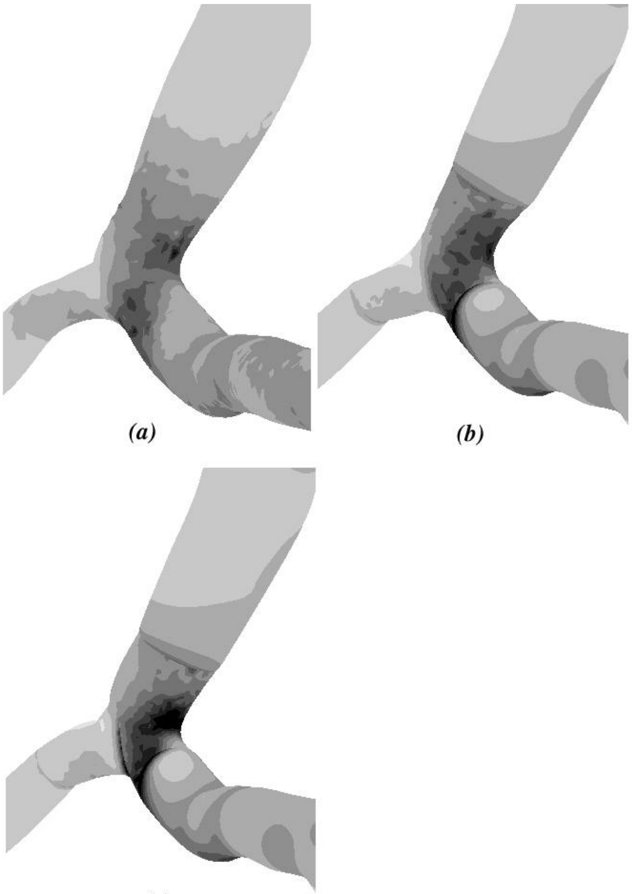
(a) (b) (c)

Figure 3. Three different versions of inserting a branch into the artery of figure 2. The wall shear stress ranges from $0Nm^{-2}$ (white) to $9Nm^{-2}$ (black).

can be constructed quickly and easily. This means that more time can be spent ensuring the junction is well constructed and meshed. This is distinct from the unstructured artery, where the entire length has to be done semi-automatically.

- The regular shape of the tubes lend themselves to a regular structured mesh. Consequently, files are smaller and calculations can be carried out faster and with less memory usage. Conversely, the shape of the junction cannot be so easily defined, and so an unstructured mesh is appropriate.
- As the 4 part method is compartmentalised, the insertion of more branches is relatively straight forward. If more branches are being inserted then only the tube in which the junction is to be placed needs to be modified.

Figures 3b and 3c were created using a different set of patches. Once the surface has been defined by intersecting the two tubes that make up the junction it is necessary to create patches on the surface upon which the mesh is placed. Depending on how these patches are placed the end shape of the junction may change slightly. Figure 4 shows a close up view of the two different junctions used to make up figures 3b and 3c with the right hand image corresponding to 3c. As can be seen in the close up views the right hand image has an unusual indentation above the branch. This indentation is not visible in the original angiograms and thus is considered an error in the meshing procedure. The meshing in the region midway between the two exit planes is also anomalous, with a high density of elements lying along a line almost perpendicular to the line between the two planes. For these reasons and others which are not visible here, the right hand mesh (and thus figure 3c) is considered unrealistic, and thus not a good model for generating wall shear stress patterns.

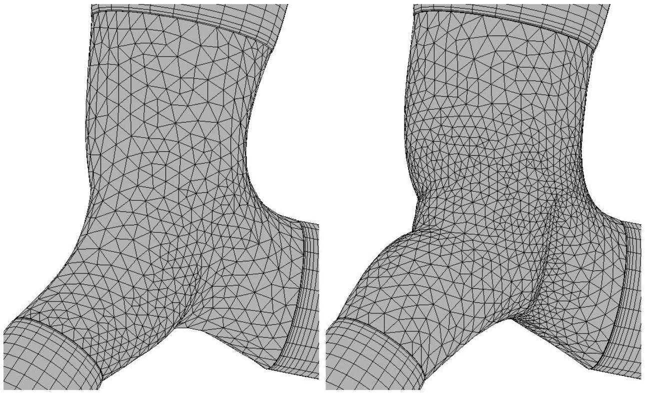

Figure 4. A close up view of the two different junctions used to make up the arteries in figure 3. The left image corresponds to figure 3b and the right to 3c

The unrealistic nature of the right hand junction in figure 4 is further emphasized by studying the wall shear stress pattern it produces in figure 3c. It is noticeably different from the other two, especially in the spread of regions of high wall shear stress. This artery illustrates the care needed when constructing branches for computational flow modelling. Every effort must be made to ensure the junction (especially) is physically consistent with the original angiograms, and does not contain any regions of inexplicably high element density.

3.2. Changes in wall shear stress throughout the cardiac cycle

Coronary arteries undergo significant conformational changes throughout the cardiac cycle. This change is often greatest in the vicinity of a junction as the different branches are pulled in different directions as the heart beats. This change results in similarly significant changes in the wall shear stress seen in the artery, once again often concentrated around a junction.

Figures 5 and 6 show wall shear stress distribution in the proximal region of an artery, branching into the LAD

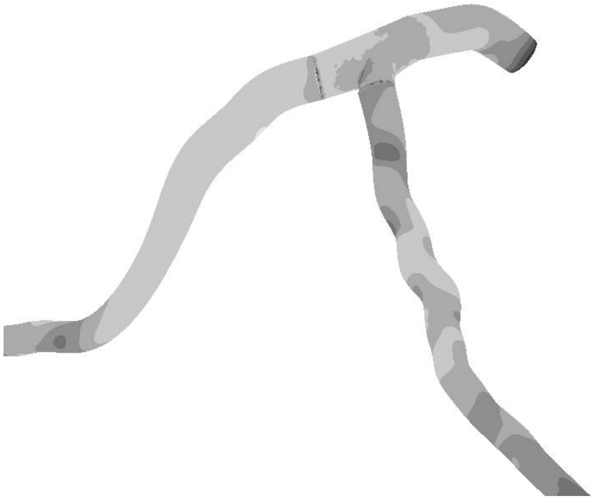

Figure 5. A left coronary artery, shown in early diastole. The wall shear stress ranges from $0Nm^{-1}$ (white) to $7Nm^{-1}$ (black).

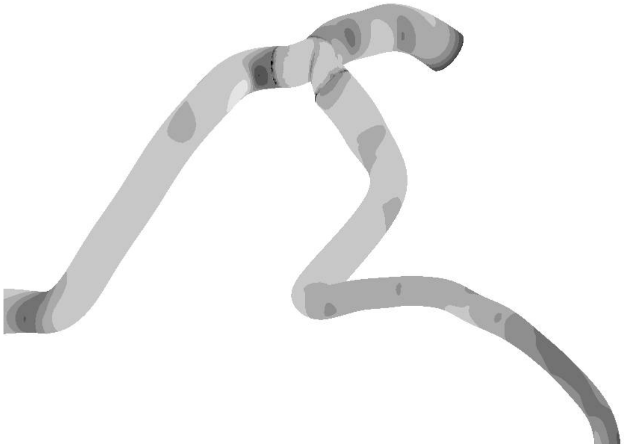

Figure 6. The same left coronary artery, but $0.32s$ later, now in mid diastole.

and LCX. The images were taken $0.32s$ apart with figure 5 corresponding to early diastole, whilst figure 6 is mid diastole. Boundary conditions are the same as for the previous artery studied. A comparison of the two images shows the variation possible in wall shear stress in a coronary artery within a short period of time. Further, the figures show that whilst the changes in wall shear stress do appear to be concentrated around the junction, they are by no means limited to this region. They also show that the spatial distribution of the shear stress cannot be easily predicted by considering a two-dimensional projection of the artery (as is the case with angiograms); the right branch of figure 5 shows far greater variation than would be expected.

4. Conclusion

A fast and efficient method for generating finite element meshes of branched arteries is essential for accurate computational modelling of blood flow in coronary arteries. It is especially important that the junctions are realistic and do not contain spurious detail or omissions. The only easy way of checking for such problems is to compare the reconstructed artery with the original angiogram images.

Wall shear stress can change rapidly due to conformational change in the coronary arteries. When studying the correlation between shear stress and the origins of atheroma it is important to consider the potential that these changes in shear stress have to affect the development of atheroma.

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