COMPARISON OF IN VIVO MRI MEASUREMENTS WITH NUMERICAL PREDICTIONS

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Abstract

Computational fluid dynamics (CFD) is increasingly used to simulate arterial blood flow in large arteries because of its ability to derive velocities and wall shear stresses, which are important parameters in correlating local haemodynamics with atherogenesis. By using a combination of magnetic resonance angiography (MRA) and CFD, in principle, the precise flow patterns of individuals can be determined. In order to assess the accuracy and reliability of this approach, CFD predictions of flow in a human aorto-iliac bifurcation are compared with in vivo MR measured velocity data. A cross-sectional plane for each vessel was chosen for comparison. Cross-sectional axial velocity profiles were compared at four time points during the cardiac cycle. Qualitative comparison of 3D axial velocity profiles revealed favourable agreement in the aorta with less than 10\% difference in peak velocities. Satisfactory correspondence was also observed in the iliac arteries with both approaches showing the same skewing of velocity profiles. This study indicated the difference between in vitro and in vivo models, and thus the need for in vivo assessment to identify areas for further refinement.

Key Words
Computational fluid dynamics; magnetic resonance imaging; aorto-iliac bifurcation; flow pattern

1. Introduction

Arterial blood flow has received much attention due to its association with the development and progression of atherosclerosis ([1], [2]). Flow related features such as low and oscillating wall shear stress, flow separation and recirculation are postulated to be associated with atherogenesis. Many in vitro experiments have been carried out in attempt to understand the haemodynamics in blood vessels ([3], [4]). However, the concept of geometric risk factors suggested that certain arterial geometric features could increase the likelihood of atherosclerosis locally by inducing flow environment that is pathogenic ([5]). The anatomic variability among individuals thus warrants the needs for patient-orientated haemodynamics study.

CFD has been extensively used to investigate the relationship between haemodynamic parameters and the development of atherosclerosis ([6],[7]). It has the ability to provide a more complete description of flow patterns in arteries, and involves a lower cost than physical testing. When allied with medical imaging techniques such as MRA, in principle, it is possible to simulate the in vivo haemodynamics of a subject. However, the complex geometry of vascular tree makes it difficult to encapsulate the in vivo haemodynamic environment using mathematical theories and equations. Moreover, wall movement and blood viscosity effects will further complicate the flow environment. Therefore, CFD predictions have to be compared with in vivo measurement to understand the level of agreement or disagreement between the two methods.

Several studies have been conducted to assess the reliability of CFD predictions using casts or phantom ([8], [9]), which show encouraging results. However, very little work has been done on in vivo models. In this paper, we present the comparison between MR velocity measurements and CFD predictions for an in vivo human abdominal aortic bifurcation.

2. Methods

2.1 Data Acquisition

A healthy 25-year old female volunteer underwent MR imaging of the distal abdominal aorta and two common iliac arteries with a 1.5T whole body MR scanner. The volunteer was scanned in the prone position. The geometry of the bifurcation was acquired with sequential 2D MR time-of-flight (TOF) angiography (TR 45 ms, TE 6.7 ms, FOV 31.8 cm, slice thickness 1.5 mm and matrix of 256 \texttimes 256). 2D segmentation was carried out to extract the vessel contour from MR-TOF images, followed by arrangement of the contours in the axial direction for 3D reconstruction and smoothing.
2.3 Velocity Data Analysis

Data analysis was performed using MATLAB. Velocities from FEMLAB and MRI measurement were compared for 4 phases of the cardiac cycle and visualised as 3D mesh plots for comparison. Only axial flow was compared since the magnitude of secondary flow was much smaller, and fell within the error margin of the measurement.

3 Results

Figures 2, 3 and 4 present comparison of the axial flow profiles in the three validation planes during flow acceleration (t/tp=0.15), peak systole (t/tp=0.25), flow deceleration (t/tp=0.35) and minimum flow phases (t/tp=0.5). Here, t is the instantaneous time, while tp is the period of the cardiac cycle (tp = 0.9231s). At the validation plane in the aorta, the agreement between MRI data and CFD predictions is quite good with the peak systole profile differed by no more than 10%. During minimum flow, the discrepancy is greater with MRI measurement exhibiting higher velocity values.

In the two iliac arteries, both approaches revealed skewed velocity profiles with slow velocities at the outer wall and high velocities at the flow divider (inner) wall. However, the amount of skewing was less in MRI data. Also, CFD predicted a blunter profile whereas MRI data exhibited a pointer shape. During minimum flow (t/tp=0.5), relatively good correspondence was observed in both planes.

4. Discussion

Knowledge of precise flow patterns in the human blood vessels is essential in helping us to understand the disease in terms of fundamental research and clinical diagnosis. Due to difficulty involved in non-invasive in vivo velocity measurements, even modern imaging techniques such as ultrasound and MRA are not able to provide adequate spatial and temporal resolution in velocity data.

In this study, we observed that discrepancies between CFD results and MRI measurements were not merely in terms of magnitude, but shape of velocity profile as well. This is different from the observations made in in vitro studies, where excellent agreement between CFD predictions and experimental measurements is usually found ([8]). One major difference between in vivo and in vitro experiments is that subject movement during scanning may degrade the quality of MRI images and introduce errors in the model reconstruction. Low velocities near the vessel wall and during diastole, as well as the partial volume effect further impair the image quality. These factors will influence both the geometry and boundary conditions used for CFD calculations. As significant amount of time is required to determine the orthogonal plane for velocity data acquisition, MRI
scanning took place over 1.5 to 2 hours. Consequently, there might be slight changes in the physiological condition of the subject. Effect of wall movement and non-Newtonian viscosity will also influence the velocity profile ([10], [11]). All these issues, which are absent in in vitro studies are believed to contribute to the less satisfactory agreement observed here.

The accuracy of geometrical model was always a concern due to the lack of ‘gold standard’. Phantom study can be used to evaluate the reliability of reconstruction algorithms, but not in investigating the accuracy of reconstructed in vivo model. Again, very good correspondence can be observed in phantom study between real and constructed model due to simplified shape, rigid wall and prior knowledge of the actual dimension. Difficulty in ensuring the accuracy of reconstructed model will introduce a lot of uncertainties, as geometry is one of the main determinants of local haemodynamics.

In CFD calculations, only a confined region of interest was modelled. Thus the effects of upstream and downstream geometry outside the region of interest were neglected. The curvature and branching of the aorta proximal to the model inlet and the common iliac bifurcation distal from the model outlets could have influenced the flow fields in the aorto-iliac bifurcation. The smaller size of iliac arteries also implied poorer spatial resolution of MRI images, and thus the increased uncertainties in image processing. Despite the above issues, the agreements in all three validation planes are fairly good.

5. Conclusion

In the present study, we have compared the CFD predictions with in vivo MRI measurements for flow in a human aortic bifurcation. The results were acceptable in the abdominal aorta and both the iliac arteries. We believe
a)  

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\begin{array}{cccc}
\text{t/tp} & 0.15 & 0.25 & 0.35 & 0.5 \\
0.19 \text{ m/s} \\
\end{array}
\]

b)

Figure 4: Axial flow profiles at the right iliac artery during flow acceleration (t/tp=0.15), peak systole (t/tp=0.25), flow deceleration (t/tp=0.35) and minimum flow (t/tp=0.5). (a) Numerical simulations. (b) MRI measurements.

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References


some of the issues discussed above can be resolved to improve the agreement between these two approaches. In this study, we have to compromise on the spatial resolution of the velocity measurement due to time constraint. Using different field of view for different velocity scans can prolong scan time significantly, especially in this case where a total of six planes were scanned. If given more time, a smaller field of view can be used on each velocity plane.

The human vascular system has a very complex 3D geometry with lots of curvature, branches and bifurcation. Using a more extensive model covering larger investigation site can reduce the inaccuracies caused by upstream and downstream geometry. Incorporating wall compliance and non-Newtonian viscosity will also enable a more realistic numerical computation.

Comparison of CFD predictions with MRI measurements in in vivo subjects enables us to determine the accuracy of numerical models used. Reviewing the sources of inaccuracy helps us to identify areas for improvement. Refined models can represent in vivo haemodynamics in atherosclerotic-prone regions more accurately, rendering CFD/MRI a more useful and reliable tool in clinical studies.

In conclusion, the good agreement achieved with in vitro and phantom studies may not be reproduced under in vivo conditions. In vivo validation of subject-specific CFD simulations revealed the needs for incorporating certain features into the numerical models, which are essential but lacking in in vitro models. Following this study, further analysis will be carried out on models implementing some of the suggestions made here.

