3D ULTRASOUND AS A BASIS FOR NUMERICAL CAROTID HEMODYNAMICS: A REPRODUCIBILITY STUDY

Fadi P. Glor (1), **Ben Ariff (2), Alexander D. Augst (1), Alun D. Hughes (2), Simon A.McG. Thom (2), Pascal R. Verdonck (3), Dean C. Barratt (2), X. Yun Xu (1)**

(1) Department of Chemical Engineering,
(2) Clinical Pharmacology and Therapeutics, Imperial College of Science, Technology and Medicine
London, UK

(3) Cardiovascular Mechanics and Biofluid Dynamics Unit, Institute of Biomedical Technology
Ghent University
Gent, Belgium

INTRODUCTION

Atherosclerosis is a focal disease. Plaque typically forms where complex flow occurs, for example in areas of marked vessel curvature and arterial bifurcations. These observations have led to the implication of local hemodynamic factors in the initiation and progression of the atherosclerotic disease process. Image-based computational fluid dynamics (CFD) has recently become a prime technique for cardiovascular research. As an imaging modality, 3D ultrasound (3DUS) has been postulated as a cost-effective alternative to the more commonly adopted magnetic resonance imaging (MRI).

Whilst we have already successfully combined our 3D ultrasound technique with CFD for in-vitro phantom studies [1] and *in vivo* studies of carotid bifurcations [2], the reproducibility of this approach in the latter case is yet to be assessed. This study was designed to investigate the reproducibility of 3D carotid bifurcation reconstruction using ultrasound, and its effects on predicted blood flow using CFD.

METHODS

Data Acquisition

Nine healthy volunteers were scanned on two separate occasions, two to four weeks apart using a 3DUS system developed in our laboratory. This system makes use of an electromagnetic tracking device, the 'pcBIRD', (Ascension Technology Inc, Vermont, USA) to track the motion of a conventional 12/5 MHz broadband linear array ultrasound transducer (HDI 5000, ATL-Philips Ltd., Bothell, MA, USA) in 3D space. The tracking device comprises an electromagnetic transmitter fixed to the side of the examination couch, and a small sensor mounted on the ultrasound probe.

During each scan, the transducer probe was swept slowly over the subject's neck. Two separate data sets were recorded: a series of ECG gated transverse 2D ultrasound images captured at mid-to-late diastole together with the position and orientation of the ultrasound probe, measured by the electromagnetic position orientation measurement (EPOM) device for each image [3].

Geometry Reconstruction

Acquired images were segmented using custom written software. The software was used to manually define points on the vessel wall to which a smooth cubic spline or ellipse was fitted, as appropriate. This spline represents the media-adventitia border. After subtraction of the intima-media thickness and centerline smoothing, a series of readjusted cross-sectional contours, defining the lumen geometry of the carotid bifurcation, were produced. Finally, the vessel inner surface was reconstructed by fitting smoothing splines to successive contour points [3].

Mesh Generation and CFD

The mesh was generated using an enhanced in-house purpose-built mesh generator based on [4]. The mesh generator constructs fully structured meshes with 50000 to 90000 hexagonal cells, depending on the lumen volume. The governing equations were solved numerically using CFX-4.4, commercial computational fluid dynamic software.

The image processing, mesh generation, the CFD data processing and statistical analysis were performed using MATLAB (Mathworks, Cambridge, UK).

RESULTS

Lumen areas were measured along the three branches in the carotid bifurcation. The average area and its deviation are shown in Fig. 1 for subjects 4 and 6, representing the worst and the best case. Average error in the CCA is 6.95 mm^2, in the ICA 2.08 mm^2 and in the ECA 1.21 mm^2, this error is attributed to the poor area agreement in only two of the nine subjects studied. Time-averaged wall shear stress

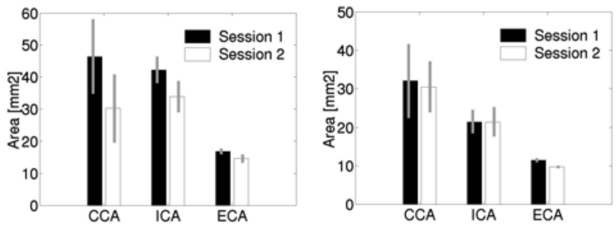

Figure 1. Mean vessel area in subjects 4 (left) and 6 (right)

(WSS) and oscillatory shear index (OSI) distributions have been linked to atherosclerosis and plaque formation. Figure 2 shows the WSS and OSI distribution obtained from session 1 and session 2 respectively for subject 8.

DISCUSSION

Areas

The mean areas (averaged along an artery) are highly reproducible, with differences less than 10% of the mean area, except in subjects 3 and 4 and around the bifurcation apex. The following possible causes for inter-session differences have been suggested. (1) Although the two scan sessions were not far apart, *physiological changes* (such as recent medication, nutrition, exercise and mental activity) could not be excluded and might have an important hemodynamic effect on cardiac output, blood pressure and cerebral blood flow. Blood pressure was measured on both occasions and no significant difference was found. However, it is possible that an individual's carotid cross-sectional area could be very pressure dependent. (2) The *diversity of the techniques* involved is considerable. Each of the techniques introduces errors due to inherent uncertainties. (3) The quality of ultrasound scan usually improves when the imaging slices are perpendicular to the vessel centerline. Because the ultrasound probe was held to follow neck skin curvature rather than carotid centerline curvature, *orthogonal orientation* could not be maintained throughout. (4) Due to the semi-automatic nature of the reconstruction technique, *operator dependency* could have an impact on the results.

Centerlines

Reproducibility of the reconstructed vessel centerlines is not as good as that of the areas. Five out of 9 subjects show important centerline differences. A likely explanation for the poor centerline reproducibility is the variation in subject's head and neck positioning between scans. Although all subjects adopted a standard scanning position, no constraint was imposed on them, hence variations in neck angles between scans could have occurred.

Time-averaged WSS and OSI distribution.

The effect on the flow of the described geometrical differences can be evaluated from Figure 2 for the WSS and the OSI for subject 8. The WSS agreement is generally satisfactory, but differences can be noticed in regions where area error is significant. Centerline variations seem to have little influence on the predicted WSS patterns, but they do have a great effect on OSI distributions. Moreover, subjects with poor area agreement but good centerline agreement, show similar OSI distributions. High OSI values correspond to regions of recirculation. Although lumen area is important in determining the magnitude of WSS, it would require a much greater difference to cause any change to OSI, whereas OSI is very sensitive to changes in vessel centerlines.

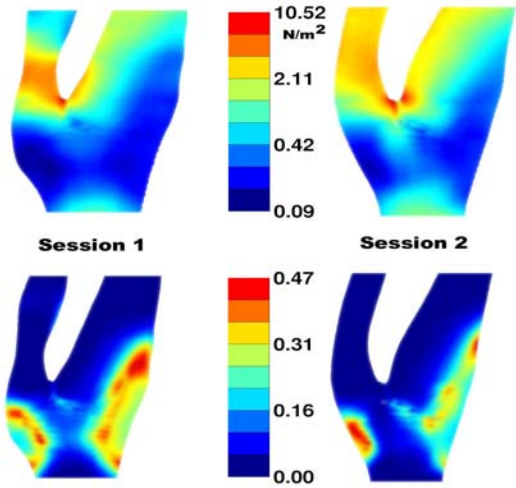

Figure 2. WSS (top) and OSI (bottom) in subject 8.

CONCLUSION

Carotid geometric reproducibility was assessed by examining area differences, area changes and centerline differences. Areas proved to be very reproducible, whereas centerlines appeared to be more sensitive. Very probably, subjects not lying in the exactly same position in the two scans is responsible for this observation. In future, the 3DUS protocol will be improved to reduce neck- and head effects as much as possible. Flow reproducibility was judged by evaluating velocities and the clinically more relevant parameters WSS and OSI. WSS and to a lesser extent OSI distributions showed satisfactory reproducibility, although WSS had a low tolerence for area-errors and OSI-distributions changed with changing centerlines. With standardisation of the ultrasound scan protocol, 3DUS is a useful and inexpensive alternative to MRI for geometry acquisition of superficial vessels.

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