EFFECT OF POSTURE CHANGE ON THE GEOMETRIC FEATURES OF THE HEALTHY CAROTID BIFURCATION

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***Abstract*— Segmented cross sectional MRI images were used to construct 3D virtual models of the carotid bifurcation in 5 healthy volunteers. Geometric features such as bifurcation angle, planarity angle, asymmetry angle tortuosity and curvature were calculated for the normal head posture and were compared to the equivalent values acquired with the head rotated clockwise by up to 80 degrees. The results obtained have shown that head rotation causes: 1) significant variations in bifurcation angle, planarity angle, asymmetry angle and internal carotid artery angle 2) tortuosity changes for the braches but not for the common carotid and 3) significant curvature changes for the common carotid artery (CCA) but not for the branches. The significant geometric changes observed in most subjects with head posture, may cause significant changes in hemodynamics and warrants future investigation of the hemodynamic parameters related to the development of atherosclerotic disease such as low oscillating wall shear stress and particle residence times.**

I. INTRODUCTION

Stroke is the third leading cause of death in the United States, accounting for 600 000 cases each year, of which about 500 000 are first attacks [1]. Several studies over the years have demonstrated that the geometry of the carotid bifurcation predicts blood flow alterations and directly influences the formation of atherosclerotic plaques [2, 3].

Recent reports [4,5] highlight the fact that peripheral arteries in parts of the body that undergo motion and posture change such as the carotid, femoral and popliteal arteries may experience changes in geometry and subsequently in hemodynamics. The influence of posture change on the geometry and hemodynamics of the carotid bifurcation has not been thoroughly studied [6]. Such changes may alter the hemodynamic variables that are generally associated with the development of atherosclerosis, such as low oscillating wall shear stress (WSS) and particle residence times.

To investigate the alteration in the geometric parameters of the carotid bifurcation with head posture change, we have performed studies on 5 healthy young volunteers. We defined specific geometric parameters of the carotid bifurcation such as bifurcation angle, asymmetry angle, planarity angle, tortuosity and curvature, and compared their corresponding values in two head postures: 1) the neutral position, and 2) a clockwise up to 80 degrees head rotation posture.

II. METHODS

A. Study group

The group of volunteers consisted of five healthy men of mean age of 35 years (range 25 to 50 years). The study was approved by the Cyprus Bioethics committee (2006).

B. MR Imaging

Magnetic resonance (MR) images were acquired using a 3T MRI instrument (Philips Medical Systems, the Netherlands). The built-in quadrature body coil and a commercially available phased array head-neck coil were used for excitation and signal detection respectively. A series of 100 thin sequential slices were obtained in the axial plane by three dimensional (3D) Time of Flight (TOF) methods, covering the entire carotid artery bifurcation and including parts of the common carotid artery (CCA), internal carotid artery (ICA) and external carotid artery (ECA). A gradient-echo (GRE) pulse sequence was implemented with TE and TR 3.5ms and 2.4ms respectively, while a flip angle (FA) of 20° was used. The acquisition voxel size was 0.36x0.36x1.2mm3 and the reconstructed voxel 0.2x0.2x0.6mm3. A parallel imaging technique (SENSE factor 2) was employed to reduce acquisition time. A variable flip angle (16-24 degrees) and gradient first moment nulling were applied to decrease the saturation effects of inflowing blood and reduce signal loss due to complex flow respectively. Each subject was imaged in the supine position and in two different scanning sessions on the same day corresponding to the two head postures examined. Two of the subjects were scanned again on a different day to allow a reproducibility study.

C. Virtual Model Development

MR images were exported in DICOM format and were converted to a single volume .img format using ImageJ (ImageJ, NIH, USA). The solid surface models were constructed by slice-by-slice manual segmentation (ITK-Snap, Paul Yushkevich, Penn Image Computing and Science Laboratory (PICSL), USA) and saved in .stl format. The 3D geometry of the carotid bifurcation was processed using the vascular modeling toolkit (VMTK) [7]. For the 3D lumen reconstruction surface, a smoothing technique from VMTK utilizing the Taubin algorithm [8] which preserves the volume enclosed by the arterial surface is used.

D. Geometric Feature Quantification

Using various features of the VMTK package, specific important geometric parameters were identified such as bifurcation angle, internal carotid artery (ICA) angle, ICA planarity angle, in-plane asymmetry angle, curvature and tortuosity. The geometric parameter definitions (Figs. 1 and 2) are as follows: Bifurcation angle is the angle between the projections of ICA and external carotid artery (ECA) vectors on to the bifurcation plane. ICA Angle is the angle between the projections of CCA and ICA on to the bifurcation plane. ICA Planarity Angle is the angle between the out of plane components of the common carotid artery (CCA) and internal carotid artery (ICA) vectors. In Plane Asymmetry Angle is defined as the difference between two angles, the angle between ICA and CCA and the angle between CCA and the ECA.

Vessel tortuosity was calculated as L/D-1 where L is the length of the centerline from the origin to the end of the branch, and D is the Euclidean distance between these two points (Fig. 2). Curvature is defined as the difference between the two unit edge vectors that connect the tree vertex. Curvature values were averaged over the length of the CCA, ECA and ICA segments of the computed centerlines.

III. Results and Discussion

Figure 1 illustrates the geometric centerlines and the vectors used for the determination of the bifurcation angle. Figure 2 illustrates the planarity angle, ICA angle, bifurcation angle and tortuosity. Figure 3 shows the virtual reconstructed models for volunteers I and II indicating gross changes in geometry with head rotation. Table I shows the absolute values of the bifurcation angle, ICA angle, ICA planarity angle and asymmetry angle for all volunteers and for both postures. Table II shows the differences between the two postures for the tortuosity and curvature of each branch. Table III shows the averaged percentage differences between the two postures for all geometric parameters studied.

The general assessment of the results is that, while there seem to be significant changes in geometric parameters with posture change in individual volunteers, these changes are random, and there is no specific tendency in a specific direction for any of the parameters in all volunteers. Bifurcation angle shows significant change with head rotation in volunteers I and III-V but little change in volunteer II. In three subjects (I, II, IV) the bifurcation angle decreased with flexion, while in the remaining two cases it increased. The ICA angle shows significant decrease again for three volunteers (I, II, IV), significant increase for volunteer IV and a minor change for volunteer III. Nevertheless, there is correlation between the two parameters regarding the direction of change. The planarity angle shows significant increase with head rotation in two volunteers, a slight increase in one volunteer and a slight decrease in the remaining two volunteers. The asymmetry angle shows significant change in three volunteers and little change in 2 volunteers. Both planarity and asymmetry angles do not correlate with bifurcation angle regarding the direction of change. The obtained results also demonstrate that rotation of the head may lead to tortuosity changes for both ICA and ECA but not for CCA. Turtuosity seems to increase in ICA with flexion, whilst head rotation seems to result in decrease of tortuosity in ECA. On the other hand, for most volunteers, curvature changes with flexion for the CCA but not for the ICA or ECA. In particular, curvature in CCA increased in four out of five subjects and decreased in one individual, whilst curvature in ICA and ECA changed in one and three subjects respectively.

Zhang et al. 2009 and Lee et al. 2008, have reported that ICA and CCA tortuosity, curvature and area ratio of ICA to ECA are important parameters in the disturbance level and formation of low/oscillating WSS regions at the carotid bulb. Our earlier studies [6], indicate that small changes in geometric parameters with head flexion can cause significant changes in the hemodynamic parameters important in the development of arterial disease.

Our present results show that in a group of 5 volunteers there are random but consistent changes in geometric parameters with posture change that may contribute to the disturbance level in the carotid bulb and the development of carotid disease.

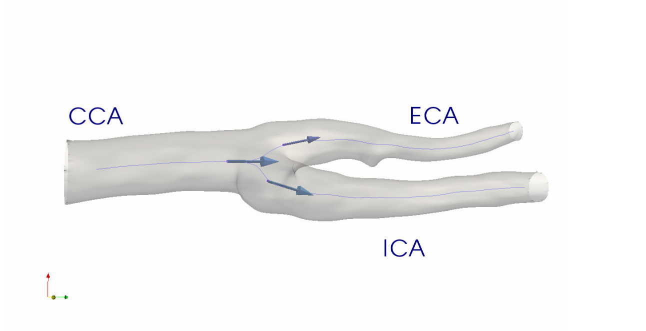

Fig. 1. Graphical representation of a reconstructed human bifurcation artery in neutral position and respective centerlines. The three vectors shown are used for the computation of bifurcation angle.

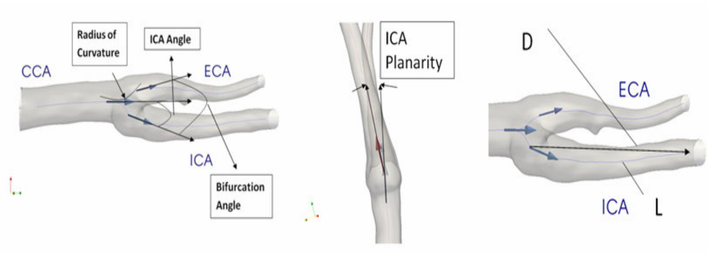

Fig. 2. Graphical representation of some of the bifurcation geometric parameters assessed in this study.

TABLE I
COMPARISON OF BIFURCATION GEOMETRIC PARAMETERS OBTAINED FROM THE TWO DIFFERENT HEAD POSTURES

Geometric Parameter (degrees)	**Subjects**	**I**	**II**	**III**	**IV**	**V**
Bifurcation Angle	Neutral	41.9	34.7	33.8	47.2	46.1
	Flexed	32.0	31.0	45.2	31.4	56.0
ICA Angle	Neutral	22.9	9.6	7.3	17.3	27.9
	Flexed	14.4	20.1	15.6	22.4	39.5
ICA Planarity Angle	Neutral	6.7	3.1	1.7	4.2	3.8
	Flexed	10.0	4.6	3.6	2.1	15.2
Asymmetry Angle In Plane	Neutral	3.9	15.5	19.2	12.6	9.8
	Flexed	3.2	9.2	14.1	13.5	23.1

TABLE II
COMPARISON OF BRANCHES GEOMETRIC PARAMETERS OBTAINED FOR THE TWO DIFFERENT HEAD POSTURES

			I	**II**	**III**	**IV**	**V**	**Mean**	**SD**
Tortuosity	CCA	Neutral	0.01	0.01	0.03	0.01	0	0.01	0.01
		Flexed	0	0.01	0.02	0.01	0.01	0.01	0.01
	ICA	Neutral	0.03	0.01	0.02	0.05	0.02	0.03	0.02
		Flexed	0.02	0.02	0.03	0.01	0.01	0.02	0.01
	ECA	Neutral	0.02	0.01	0.01	0.02	0.04	0.02	0.01
		Flexed	0.02	0.01	0.01	0.03	0.06	0.03	0.02
Curvature	CCA	Neutral	0.03	0.05	0.07	0.03	0.03	0.04	0.02
		Flexed	0.02	0.03	0.05	0.03	0.03	0.03	0.01
	ICA	Neutral	0.04	0.03	0.04	0.04	0.02	0.03	0.01
		Flexed	0.03	0.05	0.05	0.04	0.03	0.04	0.01
	ECA	Neutral	0.05	0.03	0.04	0.03	0.07	0.04	0.02
		Flexed	0.06	0.04	0.04	0.04	0.07	0.05	0.01

TABLE III
MEAN AVERAGE PERCENTAGE DIFFERENCE

Geometric Parameter		**Mean Average Percentage Difference (%)**	**SD**
Angles (degrees)	Bifurcation Angle	24.6	9.6
	ICA Angle	70.5	37.3
	ICA Planarity Angle	104.0	116.6
	Asymmetry Angle In Plane	47.7	50.1
Tortuosity	CCA	26.7	43.5
	ICA	54.7	26.3
	ECA	20.0	27.4
Curvature (1/mm)	CCA	27.0	15.7
	ICA	33.3	25.7
	ECA	17.3	16.7

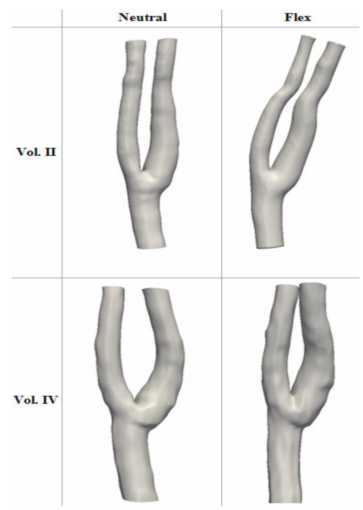

Fig. 3. Reconstructed solid models of two volunteers for the two head postures.

Accuracy and Reproducibility Studies

The assessment of the accuracy of the reconstruction procedure and the geometric parameter estimation was performed on two volunteers by: a) Repeating the segmentation and procedure for the same volunteer, and b) By following a different smoothing procedure for the acquired solid body. The segmentation procedure was repeated for two of the volunteers and the solid surface model was reconstructed for the two positions. For (a), the same surface smoothing procedure was followed in both reconstructions and the calculation of the geometric parameters. The results demonstrated that for both volunteers, the calculation of Bifurcation and ICA angle Tortuosity and Curvature in both postures showed differences less than 15%. The calculation of the ICA Planarity Angle and Asymmetry Angle show significant variations and cannot be trusted.

For (b), we determined the sensitivity of the calculation of geometric parameters with the surface smoothing procedure used. For all 5 reconstructed volunteer models, we have slightly varied the two surface smoothing parameters such as passband (from 0.04 to 0.06) and iterations (from 60 to 70). Passband is the cut-off spatial frequency of the low pass filter, and iterations is the number of smoothing passes followed by VMTK. In a similar manner, the results have shown that the calculation of Bifurcation angle, ICA angle, Tortuosity and Curvature showed close agreement with both smoothing procedures, while the calculation of ICA Planarity Angle and Asymmetry Angle showed significant differences.

Therefore, our reconstruction and smoothing procedure can produce Bifurcation angle, ICA angle, Tortuosity and curvature with confidence, but the calculation of ICA planarity and asymmetry angle is not accurate.

IV. Study limitations

The small number of individuals included in the present study constitutes its major limitation. The observed large dispersion of obtained results warrants the examination of a large cohort in order to disambiguate if there are definite trends in the change of bifurcation geometric parameters with posture alteration. In addition, the fact that a fixation system was not possible to be used during the scanning procedure has led to a varying degree of head rotation, thus contributing to a possible large dispersion of acquired results.

V. Conclusion

Despite the reduced accuracy in the calculation of planarity and asymmetry angle with posture change, our results suggest that head rotation may cause significant variation in bifurcation angle, ICA angle, planarity angle, asymmetry angle although it seems that the changes are random and depend on the geometry and elasticity of the whole neck arterial tree and there is no consistency regarding the direction and extent of change. Head rotation causes tortuosity changes for the braches (ICA and ECA) but not for the common carotid and significant curvature changes for the common carotid artery (CCA) but not for the branches (ICA and ECA). The significant geometric variations with posture change observed in most of the volunteers, may cause changes in hemodynamics and warrant future investigation of the hemodynamic parameters related to the development of atherosclerotic disease, such as low oscillating wall shear stress and particle residence times.

Appendix

Acknowledgment

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