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Proceedings of IMECE2004:
ASME International Mechanical Engineering Congress and RD&D Expo
November 13-19, 2004, Anaheim, California, U.S.A.

IMECE2004-59124

PARAMETRIC GEOMETRY DEFINITION AND ANALYSIS OF THE HUMAN CAROTID ARTERY BIFURCATION

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ABSTRACT

Three-dimensional parametric computer aided design (CAD) geometry definitions of the human carotid artery bifurcation are presented for both Y-shaped and tuning-fork models. Drawing on methods largely developed in aerodynamic design, these parametric CAD geometries are deployed within a response surface methodology to systematically map the variation of spatially integrated mean shear stress with the angles of the internal carotid artery (ICA) and the external carotid artery (ECA). Although the absolute values of this shear stress metric agree in some regions of the design space, significant differences exist in the shapes of the response surfaces for the alternative CAD models. The tuning-fork data reveals unexpected results in the location of the lowest value of the metric (at large ICA angles and small ECA angles) and also in the presence of two regions of high metric values - one, unsurprisingly, at large ICA and ECA angles but another exists close to the baseline geometry at the centre of the design space. In contrast, the Y-shaped data is such that a very spiky response surface is produced dominated by changes in the ICA angle. Also, the minimum is located at small ICA and large ECA angles. Finally, evidence is presented for strong recirculation at the outflow of the sinus bulb for small ICA angles that is non-existent for large ICA angles.

INTRODUCTION

Nearly half of all deaths worldwide are related to diseases of the cardio-vascular system. The carotid artery bifurcation (CAB) is particularly prone to the initiation and growth of arterial disease, in particular atherosclerosis. Geometry variations are believed to play a significant role in the initiation and build up of arterial disease. Numerous papers have highlighted the large variation in the shape and dimensions of the carotid artery bifurcation [1-4].

The common carotid artery (CCA) bifurcates into two branches in the neck: the ICA and the ECA. Of particular interest in the shape of this bifurcation junction is the sinus bulb on the ICA side of the geometry since this region has been recognised as the initiation site for disease within the CAB. Until recently the majority of CAB models used for computer simulations have been based on the Y-shaped model by Bharadvaj et al [1]. The tuning fork model represents a relatively new design and was highlighted by Smith et al [5] and Ding et al [1] as a more realistic model of the CAB. These observations were compared to various carotid artery bifurcations obtained from autopsies. Thomas et al [2] also highlight a preference for the design of the tuning fork model, especially for younger healthy patients.

Ding et al [1] emphasised the complexity of the flow field for the tuning fork model when compared to the Y-shaped model. An earlier study by Perktold et al [4] investigated the flow and stress behaviour in the carotid sinus for varying ICA and ECA angles. This study highlighted the difference between small and large angle bifurcation flow features with clear differences in wall shear stress behaviour.

Against this background, we attempt to better understand the relationship between haemodynamics and two key geometric parameters by systematically manipulating parametric models of the bifurcations to produce maps of the variation of the area integral of mean shear stress,

$$\overline{\tau_A} = \int \left|\overline{\tau}_{-}\right| dA_{-}$$

recently recommended in [7], where $\overline{\tau}_-$ denotes negative values of the time-averaged shear stress and dA_- signifies surface area on which $\overline{\tau} < 0$. The key to this methodology lies in the ability to automatically construct a range of related geometries by simply varying the values of parameters used to define the baseline shape [8]. The geometry definitions are too detailed to include here but will be delineated in the presentations along with details concerning the meshes and pulsatile flow simulations.

Although, in the response surface methodology, selection of points at the corners of the design space may not provide the most effective means for populating the space, it often provides a convenient way to determine suitable ranges for the design variables in preparation for more sophisticated techniques, commonly known as design of experiments (DOE) methods. Their applicability is currently under investigation.

Nine test cases for each of the CAB models were used based on the baseline mean geometry with mean angles θ_i=25.4° and θ_e=25.1° and geometries created using the standard deviation values for the ICA and ECA, σ_i = 10.4° and σ_e = 11.0°, respectively, reported in Bharadvaj et al [1].

RESULTS AND DISCUSSION

The response surface for $\overline{\tau_A}$ on the outer wall of the ICA is shown in Fig. 1 for the tuning fork model. The outer ICA wall is defined as the region between 90 and 270 degrees where 0 degrees is located on the centre line of the bifurcation divider. The surfaces are constructed using the method of kriging [9].

At large ICA angle, there is a significant increase of $\overline{\tau_A}$ with ECA angle. The maximum and minimum values of $\overline{\tau_A}$ occur, respectively, for large ICA and ECA angles and for large ICA angle and small ECA angle. Additionally, there is another peak close to the baseline design. The maximum in the Y-shaped model is also at large ICA and ECA angles but the minimum value of $\overline{\tau_A}$ occurs for small ICA angle and large ECA angle.

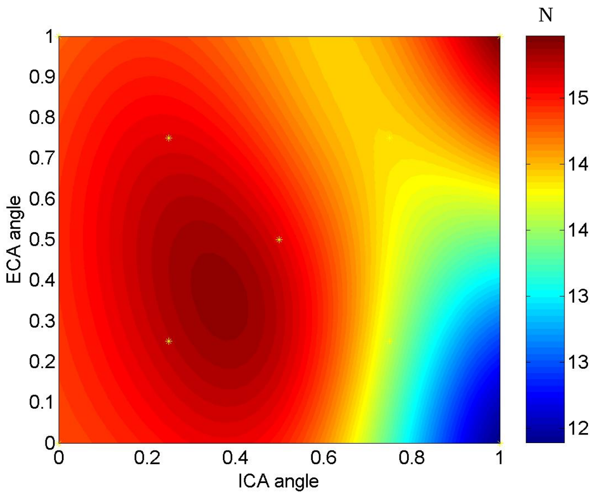

Figure 1: Area integral of negative shear stress for tuning fork model

Flow Physics

Although various contour plots and path-line visualisations were analysed, they did not reveal any evidence for the variations in $\overline{\tau_A}$. This may be due to the relatively small overall variation of $\overline{\tau_A}$ (approximately 24% of the minimum value) or it may suggest that $\overline{\tau_A}$ is not a suitable metric to capture the relationship between shear stress and the ICA and ECA angles. However, the analysis reveals that the core flow is skewed against the inner wall of the ICA sinus bulb, especially for large ICA angles, and that there are regions of reversed flow along the outer wall of the ICA sinus bulb throughout the pulse cycle (c.f. Fig. 2).

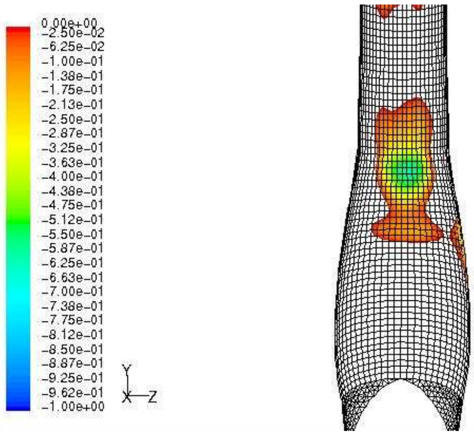

Figure 2: Negative shear stress for case 6 (small ICA angle) at t=0.3668s for tuning fork model. Units are Nm^{-2}.

Helical flow through the sinus bulb of the Y-shaped models resembles that through the tuning fork models but skewing of the flow to the outer ICA and ECA walls does not occur. The flow in the downstream branches is approximately symmetric for both sides of the CAB due to the straightness of the outflow region. Thus, although we have not been able to explain differences in the shapes of the response surfaces, we have identified a potentially important characteristic of the tuning fork model related to the interaction of the helical flow with the downstream portion of the bulb.

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