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Image-based computational hemodynamics evaluation of atherosclerotic carotid bifurcation models

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ABSTRACT

Widely accepted treatment for carotid artery stenosis includes stenting as well as carotid endoarterectomy (CEA), despite complications associated with distal embolism. Therefore pre-screening for evaluating the extent of a stenosis is critically important before undertaking surgical procedures. This study presents and evaluates the feasibility of implementing a virtual computational hemodynamics platform for clinical use to determine the severity of a stenosis and give guidance for surgical decision making. The virtual platform incorporates high-resolution three-dimensional angiography results with Computational Fluid Dynamics modeling to determine clinically related indicators. This includes wall shear stress (WSS), the spatial and temporal hemodynamic changes of blood flow within patient-specific carotid bifurcations, pressure drop coefficient, and severity stratification. The turn-around time for each computational modeling stage was examined which showed that the total time cost is practical and the proposed hemodynamics evaluation platform is reasonably efficient for clinical diagnosis. Furthermore the virtual platform may be used to detect the hemodynamic consequence of atherogenesis, which can then be addressed and quantified based on the distribution of WSS related flow indicators on the abnormal luminal fractions. Additional functional evidence and data can be used by the overseeing physician to enrich and complement the anatomical information for more in-depth evaluation of stenosis in a reasonable time duration.

1. Introduction

Atherosclerosis is a chronic disease of artery vessels whereby the artery walls thicken causing the lumen size for blood transport to narrow. It is reported that 80% of all strokes that occur annually in the western world are ischemic and around 30% of these are due to thromboemboli arising from atherosclerotic lesions at the carotid artery bifurcation [1]. As atherosclerosis can remain asymptomatic for decades [2], accurate prevalence and incidence rates of carotid artery stenosis (CAS) are difficult to ascertain. Therefore, the consequence of CAS can be easily underestimated as many patients do not seek medical attention despite having CS for a prolonged period.

The diagnosis of symptomatic CAS relies on a combination of history, clinical examination and imaging derived from CT, MR imaging, ultrasonographic and angiographic images. The evaluation of angiographic images is limited to the geometric measurement determining the degree of stenosis, leaving the ultimate stenosis evaluation to the experience of the treating physician. For symptomatic patients who undertake carotid endarterectomy, the risk of fatal stroke to a severe CAS is reduced to 13% over 2 years [3]. The report by the ECST Group [3] concluded that while a strong correlation exists between severe CAS and stroke incidence, using anatomical stenosis geometry as a single indicator of risk of stroke is poorly justified. In addition, even a thorough clinical history record can further assist the physician to assess stroke risk. Due to the wide range of treatment options, a reliable way has to be found to select the most appropriate option for each patient.

Taxon [4] has shown that frequent occurrence of localized atherosclerotic plaques in curvature, bifurcation, and branching of arterial vessel regions suggest that fluid dynamics and vessel geometry may have an influence in plaque formation. Computational fluid dynamic (CFD) methods can offer additional functional information from a hemodynamics point of view to complement the vessel geometry information, detailed *in-vivo* angiographic imaging or *in-vitro* experimental velocimetry measurements.

Many numerical hemodynamic studies have been performed to investigate the hemodynamic influence on CAS progression, which has established that the magnitude and gradient of blood flow near the vessel wall, or the wall shear stress, is a source of pathogenesis of CAS [5–7]. Vessels exposed to low wall shear

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stress appear to be more prone to plaque development based on an MR imaging based study using 21 carotid arteries [6]. Researchers determined that the investigations of local risk indicators such as time-averaged wall shear stress (TAWSS) and oscillatory shear index (OSI) in atherosclerosis did not rely on all the surrogate geometric markers of disturbed flow [7]. While atherosclerotic disease is a multifactorial disease, hemodynamic forces and wall shear stress mapping can provide a complementary determinant among a multidisciplinary approach for early atherosclerosis detection. Therefore obtaining such data must be prompt in order for it to be of clinical use.

Although numerous studies of carotid artery bifurcations have been performed, most have concentrated on analyzing the blood flow pattern within the stenotic district through various modeling assumptions, such as steady flow [8], pulsatile flow [9], rigid vessel [10], compliant vessel [11], Newtonian flow [12], non-Newtonian flow [13,14], and anatomical effects, including artery branching [15], bifurcation angles [13,16] and wall curvature [17]. LaDisa et al. [18] have numerically examined the influence of WSS and OSI in progression of plaques in a clinically reasonable time-frame. However, the hemodynamic burden (effect on blood flow transportation) caused by the existence of the plaque was not investigated, which is an important practical indicator in helping the treating physician for carrying out risk stratification and arranging appropriate treatments.

In order to reveal the stenotic lesion burden and its influence exerting on the blood flow transport in an efficient time, as many assumptions as possible should be accounted for while omitting those that are less relevant and are time consuming. This will allow an efficient CFD based diagnosis assistance platform for atherosclerotic carotid bifurcation treatment as a step towards improving surgical planning and therapy outcomes. In this paper, a robust and time-efficient computational hemodynamics platform is proposed, and clinical related indicators are introduced for data processing and severity stratification of CAS. Ten carotid artery bifurcations were reconstructed from MR scans, and intravascular flow patterns were predicted using CFD analysis with a fine structured mesh and a non-Newtonian viscosity model. The stenosis-induced flow performance and the flow disturbance in pre-stenosis and post-stenotic regions were examined and this was integrated with high resolution anatomical measurements for direct and long-term plaque burden evaluation. Each step in the work flow was monitored for reproducing reasonable results with a minimized time cost. This proposed framework is a step towards an e-health platform that can assist both doctors and patients to have a better understanding of CAS disease and to provide better guidance for clinical treatment.

2. Methodology

Patient-specific realistic carotid bifurcation models were reconstructed from MR image data and their corresponding stenosis severity were anatomically assessed. Then, a computational hemodynamics approach was proposed and performed on these patient-specific carotid bifurcation models. Prior to that, the numerical accuracy of the proposed modeling approach was evaluated through comparison of numerical and experimental results on the basis of two standard idealized carotid bifurcation models. Finally, the hemodynamics performance and computational efficiency were examined for clinical diagnostic purposes.

2.1. MR imaging

High resolution MR imaging of carotid bifurcations was performed on patients using a 1.5 T General Electric scanner. All human experiments were approved by the Monash Medical Center and an Institutional Review Board. The MR imaging was first performed on four patients, which constitute a total of eight models that pertain to their left and right carotid bifurcations. Then another two additional carotid bifurcation models were scanned from two additional patients of which only one artery from each pair of carotid arteries were selected. Altogether, ten patient-specific models were imaged from six patients. For each carotid artery, a total of 112 contiguous slices were generated from the high-resolution T-1 weighted spoiled gradient echo with parameters as follows: TR, 35 ms; TE, 7 ms; flip angle, 35°; field of view, 24 cm; voxel size 0.63 mm × 0.73 mm × 0.63 mm.

2.2. Arterial model reconstruction

Based on the MR imaging data, the computational model was reconstructed using a commercial software Mimics (Materialise HQ, Belgium). The specific structures of interest were extracted out based on a thresholding range of gray scale values in the segmentation process. This approach separates the luminal area from the rest of the tissues. Though this is a simple technique, there remain factors that can complicate the thresholding operation. For example, non-stationary and correlated noise, ambient illumination, busyness of gray levels within the object and its background, inadequate contrast, and object size not commensurate with the scene. All these factors require considerable manual operation during the segmentation process. A 3D model is then exported as a '.stl' (stereolithography) file. Fig. 1 shows the ten patient-specific carotid artery models that were produced. The common carotid artery (CCA), internal carotid artery (ICA) and external carotid artery (ECA) are labeled for each model. In addition to these patient specific models, two standard geometry models are created. These standard idealized stenotic model are the 63% ICA stenosis averaged tuning-fork shaped human carotid bifurcation (ST-AHCB) model, and the plain tuning-fork shaped human carotid bifurcation (TF-ACHB) [19]. These models will be used as a benchmark model for comparisons, as it is well-defined and has been used extensively in the literature. A schematic diagram of these two idealized carotid bifurcation models is illustrated by Fig. 2, and their detailed dimensions are given in Table 1.

2.3. Anatomical assessment

Anatomical measurements to obtain two characteristic parameters, stenosis diameter *A* and distal diameter *B* were performed on each model and the values presented in Table 2. A schematic diagram of an artery stenotic region is shown in Fig. 3 to highlight the characteristic parameters.

In clinical trials, one way to estimate the degree of carotid stenosis is to calculate distal diameter reduction (DDR) through comparing the diameter of the residual lumen at the site of the stenosis (variable *A* in Table 2) to the diameter of the distal unaffected lumen (variable *B* in Table 2) [20], and the degree of stenosis for the studied carotid models examined by DDR method are shown in Table 2. It is found that nine models were experiencing one or two sites of stenosis except model 9, which exhibited no significant diameter variation in its radial direction. In terms of pathological location, six models (models 2 and 4–8) suffered stenotic lesions on the ICA; two models (models 1 and 10) presented stenotic lesions on both ICA and ECA, while only one model (model 3) had a CCA stenosis. In terms of stenosis severity, four carotid models (models 1–3 and 6) experienced larger than 50% DDR in their stenosis lesions, and model 2 was suffering a DDR of 71.58% at its ICA branch, which is the most severe case among all models.

However, the generated anatomical information does not represent a dynamic stenosis burden under transient blood flow, and a further analysis of stenosis-induced influence on arterial blood flow transportation will be much more functional in clinical