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Assessment of Carotid Stenoses by the Principle of Fractional Flow Reserve Derived from CT

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Abstract: The content of the study is focused on multiscale modelling of pulsatile non-Newtonian blood flow in patient-specific models of complete carotid bifurcations. The modelled flow parameters, especially those of outlet Windkessel models, are tuned on the basis of in-vivo measurements provided by the courtesy of the University Hospital Pilsen. The process of tuning is carried out by utilising corresponding 1D models of the carotid bifurcations. To assess the physiological significance of atherosclerotic lesions present in the models, a novel non-invasive variant of the fractional flow reserve method known as FFR_{CT} is used.

Introduction

The use of computer-aided imaging methods such as the computed tomography (CT) angiography has opened up new possibilities in the detection and assessment of hemodynamically significant carotid stenoses, which are often the primary cause of brain stroke in the European population. Although the use of CT enables a direct visualisation of the damaged arterial segment, this noninvasive imaging technique is not always reliable as it shows a tendency to overestimate the stenosis severity and its hemodynamical significance [1]. To avoid the inaccuracy and to use the full potential of CT, a novel noninvasive technique known as the fractional flow reserve derived from CT (FFR_{CT}) has been developed and successfully tested for the assessment of lesion-specific coronary ischemia [1, 2]. Basically, the noninvasive assessment of stenosis severity based on FFR_{CT} is also applicable to peripheral arteries including the carotid ones, where the knowledge of flow field distribution provided by the tools of computational fluid dynamics (CFD) in combination with anatomic image data shows the potential to improve the difficult diagnosis of stenoses of intermediate severity (40 – 70% lumen reduction).

Following the idea of FFR_{CT} described in detail, e.g., in [2], the present study is focused on the development of a CFD-based tool that would be able to perform multiscale patient-specific simulations of carotid artery fluid dynamics and provide a better insight into the hemodynamical significance of stenoses identified in patient-specific models of complete carotid bifurcations.

Multiscale modelling

For the purpose of the study, several different patient-specific models of stenosed carotid bifurcations (Fig. 1a) are obtained with the help of the in-house segmentation/meshing software DICOM2FEM [3]. Considering the complexity of the flow problem, the numerical simulations of pulsatile non- Newtonian blood flow are carried out on the basis of several simplifications such as the assumption of inelastic model walls and blood's non-Newtonian rheology described by the shear-dependent Carreau-Yasuda model [4]. The mathematical model given by the non-linear system of incompressible Navier-Stokes equations is numerically solved using in-house software based on a stabilised variant of the

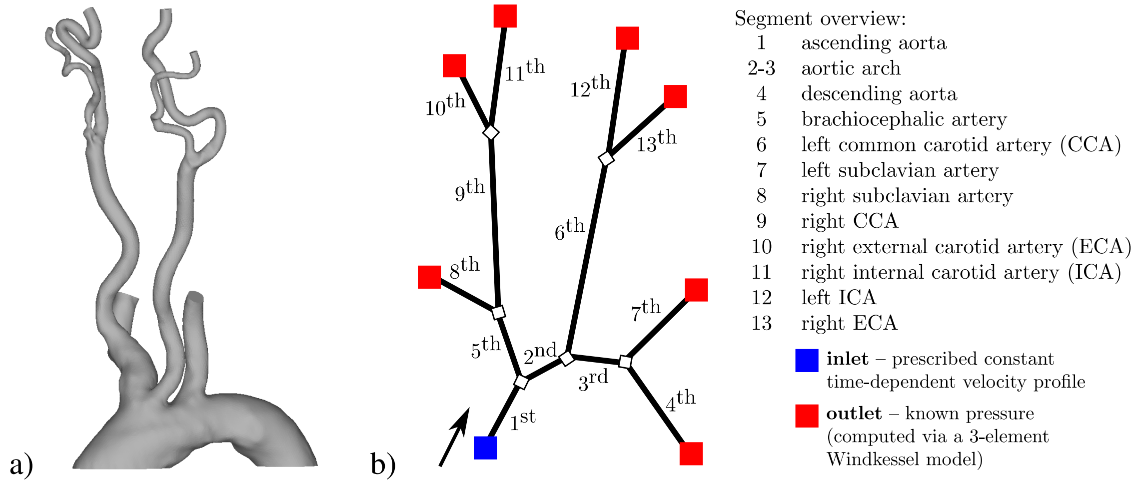

Fig. 1: (a) 3D and (b) 1D representations of a patient-specific model of carotid bifurcation.

projection method in combination with the cell-centred finite volume method formulated for hybrid unstructured tetrahedral grids. For the details, see [5].

Similarly to other flow problems, the quality and accuracy of computed results can be influenced by the inlet and outlet values prescribed at corresponding boundaries of the computational domain. As the clinical determination of physiological pressure at relevant parts of the cardiovascular system is difficult to perform, this study approaches this problem by adding a 0D model (*three-element Windkessel model*) to each arterial model outlet, where it can simulate the flow resistance of a real downstream vascular bed and provide a physiological pressure value. The Windkessel parameters are estimated in an iterative manner on the basis of in-vivo measurements provided by the courtesy of the University Hospital Pilsen. To achieve a flexible and computationally efficient estimation process, the 3D arterial models (Fig. 1a) are substituted with their 1D representatives (Fig. 1b) in accordance with the approach described and tested in [6].

The analysis and discussion of obtained numerical results, including the assessment of relevant carotid stenoses, is carried out with the help of two well-known hemodynamical wall parameters (the cycle-averaged wall shear stress, WSS, and the oscillatory shear index, OSI) and the already mentioned FFR_{CT}, principle of which is similar to that of its invasive counterpart (FFR). In other words, the hemodynamical significance of a stenosis is determined on the basis of pressure difference before and after the arterial narrowing ($FFR_{CT} \leq 0.8$ indicates ischemia [1]).

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