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Original Research Article

Computational simulation of carotid stenosis and flow dynamics based on patient ultrasound data – A new tool for risk assessment and surgical planning

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ABSTRACT

Purpose: There is nowadays extensive experimental and computational investigation on the pathophysiology of atherosclerosis, searching correlations between its focal nature and local hemodynamic environment. The goal of this work is to present a methodology for patient-specific hemodynamics study of the carotid artery bifurcation based on the use of ultrasound (US) morphological and blood flow velocity patient data.
Materials/methods: Subject-specific studies were performed for two patients, using a developed finite element code. Geometrical models were obtained from the acquisition of longitudinal and sequential cross-sectional ultrasound images and boundary conditions from Doppler velocity measurements at the common carotid artery.
Results: There was a good agreement between ultrasound imaging data and computational simulated results. For a normal and a stenosed carotid bifurcation the velocity, wall shear stress (WSS) and WSS descriptors analysis illustrated the extremely complex hemodynamic behavior along the cardiac cycle. Different patterns were found, associated with morphology and hemodynamic patient-specific conditions. High values of time-averaged WSS (TAWSS) were found at stenosis site and for both patients TAWSS fields presented low values within areas of high oscillating shear index and relative residence time values, corresponding to recirculation zones.
Conclusion: Simulated hemodynamic parameters were able to capture the disturbed flow conditions in a normal and a stenosed carotid artery bifurcation, which play an important role in the development of local atherosclerotic plaques. Computational simulations based on clinic US might help improving diagnostic and treatment management of carotid atherosclerosis.

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1. Introduction

Many studies looking for correlation between local hemodynamics and development of atherosclerosis have been done. Artery bifurcations and curvature regions are prone sites to develop initiation of atherosclerotic plaques, and often present disturbed wall shear stress and flow disruption [1–5]. The common carotid artery (CCA) bifurcation and the proximal external (ECA) and internal (ICA) carotid arteries are prone sites to atherosclerosis associated diseases. Several studies point to a complex interrelationship among vascular geometry, local hemodynamics, vascular aging, and atherosclerosis [2,6–9]. Although the relationship between carotid plaque morphology and stroke pathogenesis is not yet fully understood it is widely accepted that the wall shear stress (WSS) plays an important role in the development and progression of atherosclerosis. WSS within the stenosis is usually high due to flow acceleration in the reduced lumen. Diseased vessels and post-stenotic regions experience a significantly different biomechanical environment than healthy vessels, due to high Reynolds numbers and the presence of transitional and

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turbulent flow, which may be responsible for cell damage or plaque disruption [3]. Namely the presence of turbulence associated with high WSS and large spatial WSS gradient is thought to enhance mass transport into the arterial wall and make the plaque vulnerable to rupture [3,4,10].

Most studies aiming to investigate turbulent flow characteristics within stenosed vessels were conducted experimentally and employing numerically idealized stenosis geometries [10–13]. Image-based computational fluid dynamics (CFD) studies of real arterial anatomical geometries appeared in the late 1990s, either using computed tomography (CT) and magnetic resonance imaging (MRI) [14–20], or ultrasound (US) imaging [21–24]. Non-invasive and inexpensive ultrasound imaging is a widely used instrument for medical diagnosis of arterial diseases, like atherosclerosis; furthermore CCA bifurcation is quite superficial and allows real-time images of endovascular structure with high spatial resolution, and in vivo measurements of velocities with minimal risk for the patient [12,25–27].

Blood flow velocity spectral waveforms at the carotid arteries of older adults are significantly different from those of young adults [28]. For an older adult a common feature is the presence of a strong secondary peak during early systolic deceleration, typically associated with flow disturbances. While for large-scale studies of CCA bifurcation hemodynamics the use of a typical flow waveform shape is sufficient [10,12,20,28], for a single patient study a subject-specific waveform collected in clinical practice yields a more accurate assessment of flow characteristics. Furthermore for image-based hemodynamics studies, the carotid artery domain of interest is always truncated and the application of the inlet and outlet boundary conditions will affect the numerical accuracy of the WSS derived parameters dramatically [17,28,29].

Selecting patient specific CCA bifurcation with stenosis, as diagnosed by ultrasound, the present investigation developed a platform that will provide estimates of disturbed flow conditions and forces at the carotid artery wall toward the link between hemodynamic behavior and stenosis pathophysiology. Computational simulation of detailed morphological and hemodynamic carotid bifurcation characteristics was performed using an ultrasound based semi-automatic methodology for reconstruction and structured meshing, and the incompressible Navier–Stokes equations for blood flow modeling. Post-processing results showed WSS and its descriptors to be extremely sensitive to variation in geometry enabling early detection of vessels at risk and prediction of stenotic disease progression. Furthermore, specific carotid bifurcation hemodynamic analysis could be used to model/replicate turbulence conditions at high-grade stenosis where the velocity is very high and ultrasound measurements can suffer from inaccuracies.

The present research was partially done in the scope of a project with a public hospital using simple, inexpensive and non-invasive carotid artery US as a preliminary diagnostic tool for artery disease. Hemodynamic simulation post-processing will allow accurate characterization and identification of patients with high probability for developing cerebral vascular events.

2. Materials and methods

The computational investigation of patient specific arterial morphology and blood flow behavior using a finite element code requires four sequential steps [30]: (1) acquiring ultrasound morphological and blood flow velocity data of patients' carotid artery cervical segments, (2) reconstructing a computational surface of the ultrasound-based carotid image, (3) defining a 3D finite element mesh and (4) performing a computational blood flow simulation.

Aiming to study complex flow features near the stenosis two patients volunteered to participate; Patient 1 (P1) was a 57-year-old man with a CCA bifurcation stenosis, and for inter-individual comparison, patient 2 (P2) was a 63-year-old man with no visible carotid atherosclerotic plaque.

Data was obtained at São João Hospital Centre, a university hospital in Porto, Portugal. The study was approved by the institutional ethical committee and informed consent of each volunteer was obtained. Carotid artery examinations were performed according to a proposed created protocol.

2.1. Acquisition of ultrasound morphological and blood flow velocity data of patients' carotid artery cervical segments

Experimental data necessary for the present study were obtained by the same experienced sonographer (R.S.) dedicated to neurovascular ultrasound at the Neurosonology Unit of the Department of Neurology of São João Hospital Centre [30].

Using a commercial color ultrasound scanner (Vivid e; GE, Milwaukee, WI, USA) and a linear array probe (GE 8L-RS), high-resolution ultrasound images with 256 level of gray scale and pulsed-wave Doppler PW were collected along the CCA, its bifurcation and proximal segments of ICA and ECA from approximately 2 cm before CCA bifurcation, until post-bulbar ICA and ECA, including the bifurcation entrance (APEX). Raw DICOM data were exported from the echography device for offline analysis.

The longitudinal and transversal set of B-mode images were recorded at end-diastole, to control physiologic variations of diameter within cardiac cycle. End diastolic point was visually identified selecting the video frame of the instant of minimum artery diameter. Cross-sectional locations were registered at the longitudinal bifurcation image, to allow the correct reconstruction of the CCA bifurcation luminal surface. In order to minimize flow modeling inaccuracies, tracking of the US probe was done by marking positions along the artery bifurcation relying on the ability to manually guide the US probe. During medical examination of patient P1, ICA stenosis was measured according to European Carotid Surgery Trial (ECST), the percentage of luminal diameter narrowing at the most stenotic region.

Using US pulsed-wave (PW) mode with a 2 mm sample volume, axial flow velocity waveforms were obtained at several specific locations from 2 cm before CCA bifurcation to the most distal region of ICA and ECA arteries that could be measured with angle of insonation $\leq 60^{\circ}$. For each patient flow velocity waveforms obtained from PW images were collected using Matlab. Considering waveform data from three cardiac cycles Fourier analysis allowed the determination of the first seven harmonics coefficients used to set Womersley profiles. Early and mid-diastolic minima and peaks of flow velocity waveforms were found by a forward search from systolic peak for changes in the sign of the derivative. The mid deceleration phase was considered to be the cardiac cycle instant corresponding to half-peak midway between systolic peak and first early-minimum [31].

2.2. Reconstruction of a computational surface of the ultrasound-based carotid image

Given a series of 2D longitudinal and cross-sectional images of the common carotid artery bifurcation, the most obvious method of reconstruction was to outline, either manually or automatically, the boundaries of the lumen and of the artery wall to produce a skeleton of the vessel [30].

The selected 2D longitudinal and cross-sectional images were manually segmented by two neurosonologists (EA, PC). In the plaque region, two contours were delineated for each cross-sectional image,

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