ABSTRACT
Non-invasive ultrasound imaging of human arteries is a widely form used for medical diagnosis of arterial diseases, like atherosclerosis. The objective of this paper is to present a methodology for patient-specific construction of a structured mesh of the carotid artery bifurcation from images obtained with Doppler ultrasound techniques.

Keywords: three-dimensional reconstruction, mesh generation, arterial bifurcation

INTRODUCTION
Atherosclerosis can be quantitatively evaluated by the intima-media thickness (IMT), which measures the distance between the inner boundary of the adventitia and the lumen, the region of the vessel where the blood flows. Colour Doppler ultrasound provides real-time images of endovascular structure and measuring techniques have improved to provide accurate information on the flow fields. Furthermore ultrasound imaging presents minimal risk for the patient (Schumann et al., 2008; Rocha et. al., 2010). The IMT of extra-cranial carotid arteries can be measured using B-mode imaging and provides an index of individual atherosclerosis which is used for cardiovascular risk assessment in clinical practice.

The objective of this paper is to present a semi-automatic methodology for patient-specific reconstruction and structured meshing of the left carotid bifurcation using Doppler ultrasound images. The proposed methodology also represents a tool to generate structured computational meshes for vascular modeling frameworks. Similar methodology for mesh generation using coronary angiography data has been published by De Santis (De Santis et al., 2010; De Santis et al., 2011). Using patient-specific carotid artery bifurcation data the generation of a structured and conformal hexahedral mesh of a nearly-planar carotid bifurcation is presented.

The ultimate aim of this study is the reconstruction of geometry and flow environment from in-vivo patient data, particularly at the extra-cranial carotid arteries, using Doppler ultrasound data.

METHODS
Three main steps were involved in developing the carotid bifurcation mesh model:

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STRUCTURED MESH GENERATION FROM DOPPLER ULTRASOUND IMAGES
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(1) acquiring the in vivo anatomical data of the diseased arterial segment via ultrasound imaging; (2) image surface reconstruction; (3) 3D finite element mesh definition.

ACQUISITION OF ANATOMICAL IN VIVO GEOMETRY

A set of longitudinal B-mode images of the common carotid artery and the carotid bifurcation of an elderly patient was acquired with a standard commercial colour ultrasound scanner (General Electric vivid e) and recorded with 256 grey levels. The resolution was normalized to 0.09 mm, a common value used in clinical practice. Completeness of the data was achieved with cross-sectional ultrasound images obtained in sequence along the common carotid artery and the carotid bifurcation.

All the images were then processed by a PC allowing near real time viewing of the images. Fig.1 presents a carotid bifurcation image obtained using B-mode ultrasound. Areas of blood flow appear darker than surrounding tissue and their contours can be isolated by visual thresholding. At the image the medical doctor was able to make a rough measurement of the intima-media region boundaries. Further definition of the arterial geometry was based on in vivo image data with minimum volume at diastolic pressure.

GEOMETRICAL 3D SURFACE RECONSTRUCTION

After importing the 2D image into the modelling software FEMAP, an obvious method of reconstruction is to outline, either manually or with computer assistance, the boundaries of the lumen and, if available the outer wall, to produce a skeleton of the vessel. Then, specific points on the boundary are considered in order to construct splines A, B, C and D defining an estimated lumen boundary for the Internal Carotid Artery (ICA), the External Carotid Artery (ECA) and the Common Carotid Artery (CCA) as shown is Fig. 1.
In order to guarantee that the surface reconstruction at the intersections of ECA and ICA with CCA are performed continuously, C and D splines are extended using auxiliary lines that are tangent to those splines at their intersection point. Points defining the tangents are presented in Fig. 2.

2D ultrasound images are acquired manually without reference to a fixed coordinate system, making difficult the spatial reconstruction. A convenient reference axis was adopted considering the distal CCA entrance cross-section belonging to the yOz plane.

The central axes of the CCA, ECA and ICA were defined at the (x, y)-plane by creating a curve associated to equidistant points from splines A to B, A to C and D to B and considering their tangent auxiliary lines (Fig. 3). All three central axes are due to converge at one single point. Then, assuming CCA, ECA and ICA as cylindrical vessels, except at their junctions, artery cross-sections were considered circular as a function of the length of each central axis (Fig. 3) with diameters given by the B-mode ultrasound data. The definition of this model was improved using measurements from cross-sectional ultrasound images.
For the 3D reconstructing process of the carotid bifurcation geometry, cross-sections of ICA and ECA junctions are the result of overlapped cross-sections, defining non-circular sections. Fig. 4 describes this process.

Finally the surface of the bifurcation is built with FEMAP function “Aligned Curves”. The process is repeated for each of the three different branches, ICA, ECA and CCA, respectively, as presented in Fig.5.
The success or failure of this 3D reconstruction methodology is dependent on the correct setting of cross-sections as shown in Fig. 3. These sections should be parallel and evenly spaced. Fig. 6 presents a diagram with the main steps of the proposed 3D surface reconstruction methodology.

The reconstructed surfaces will be used as input to a computational fluid solver and geometric analysis tools. The ability to perform accurate flow simulations based on vessel geometry is fundamental to help surgeons to determine the appropriate intervention. So, the achieved domain should be artificially extended by a few diameters at both arterial inlet and outlets to remove the direct influence of the boundary conditions on bifurcation blood flow simulations.
STRUCTURED MESH GENERATION

Following De Santis (De Santis et al., 2011) a structured hexahedral mesh of the lumen of the nearly-planar carotid bifurcation was constructed and is presented in Fig. 7. Hexahedral meshes are generally more difficult to generate, and the associated operator intervention time is expensive. On the other hand, for the same accuracy of the result, computer simulations using hexahedral meshes compared to tetrahedral/prismatic meshes converge better, less computational time is required, and they are superior for the calculation of the wall shear.

Using software FEMAP the generation of the volume mesh with hexahedral elements started by defining three confining cross-sections created as artificial separations of the CCA, ECA and ICA branches at the bifurcation. Then the filling of the previously defined surface geometry was performed by dividing the domain in six parts and each part meshed independently maintaining finite elements continuity at each contact surface as shown in Fig. 7.

The CCA, ECA and ICA branches are treated independently according to the following procedure: first, a 2D quadrilateral mesh is considered in a defined cross-section; then, by sweeping or extruding a 2D mesh of a section (quadrilateral) along a path, a volume mesh is generated (hexahedrons). At the intersections of ECA and ICA with CCA meshing is performed by superposing common nodes and elements. Fig. 7 presents selected lumen sections exhibiting the square-based pattern (buttery) used at each quadrant of the inner part of the lumen. By distributing the elements according to the desired accuracy, the local refinement of a hexahedral mesh has the potential to speed up highly demanding computations on large arterial territories.

ACKNOWLEDGMENTS
This work was partially done in the scope of project PTDC/SAU-BEB/102547/2008, “Blood flow simulation in arterial networks towards application at hospital”, financially supported by FCT – Fundação para a Ciência e a Tecnologia from Portugal.

REFERENCES


