Assessment of the Rupture Risk of Abdominal Aortic Aneurysms by Patient-Specific Hemodynamic Modeling - Initial Results

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Introduction

At present, the diameter of an abdominal aortic aneurysm (AAA) is considered to be the primary indicator of rupture risk. Surgical treatment is usually performed if the diameter exceeds 5 cm. Rupture does however occur for diameters less than 5 cm. We therefore investigate if better rupture risk indicators can be obtained by patient-specific hemodynamic modeling. This paper discusses the steps involved in this modeling and it describes our approach and first results for each of the steps.

Materials and Methods

Hemodynamic modeling of an AAA involves a number of steps: 1) 3D imaging of the abdominal aorta, 2) determination of the 3D geometry of the various components of the AAA from the acquired images, i.e. lumen, thrombus, wall and calcifications, 3) volume meshing, i.e. discretization of the 3D geometry, 4) formulation of the discrete equations that describe the blood flow dynamics and the wall mechanics by means of a finite element method, 5) specification of the boundary conditions for these equations and the material properties of the aorta components involved in the modeling, 6) solving of the equations by means of a computer, 7) visualization and interpretation of the simulation results.

Conventionally, CT Angiography (CTA) is used to derive the geometry of the lumen, thrombus and calcifications. CTA does however not supply information about the geometry of the aorta wall and has difficulties with triggering the image acquisition to the cardiac cycle. We consider information about the wall to be essential for rupture risk prediction. We have therefore developed specific MRI protocols for imaging of the lumen, the thrombus and the wall. We have furthermore developed a specific MRI protocol for measuring the blood flow at the input and the output of the AAA (the flow boundary conditions needed for the flow simulation). Calcifications could potentially be visualized by MRI (dark regions), but at the moment they can be more easily obtained from CTA images.

For the segmentation of the various AAA components we have investigated the technique of 3D Active Objects (3DAO) [1], the 3D analogy of 2D Active Contours [2]. The result of this type of segmentation is a surface description for each of the AAA components. We have developed special meshing software for the translation of these surface descriptions to the required volume meshes.

We have modeled the aortic blood flow with the Navier-Stokes equations and we have assumed linear elastic wall material. The local blood flow through the aorta as function of time in the cardiac cycle was calculated by means of computational fluid dynamic (CFD) simulations and the displacement of the aorta wall and the strain and stress in the wall were calculated by means of computational solid mechanics (CSM) simulations (Finite Element Modeling package Sepran, Delft University of Technology, The Netherlands). The CFD/CSM simulations result in large amounts of data: local blood flow velocity and pressure in the aorta, local wall displacement, local strain and stress in the wall. We have developed special software for the intuitive visualization of these data.

Results

Figure 1 shows one slice through an AAA obtained with the developed MRI protocols and with CTA. We have found that MRI is well suited for the determination of the information needed for the CFD/CSM simulations, since the lumen, thrombus, wall (including motion) are well visualized by MRI and the flow can be quantified with MRI. Figure 2 gives an example of the result of a 3DAO-based segmentation of the lumen geometry and figure 3 shows a tetrahedral volume mesh that was derived from this geometry. Figure 4 shows a colour overlay of the computed wall stress. This simulation was performed on a mesh with circular cross section, filled with hexahedral volume elements. Thrombus and calcifications were not yet included and healthy (constant) values were assumed for the wall thickness and wall elasticity. Furthermore, a constant blood pressure was assumed.

Discussion and conclusions

Our simulations show that even for a wall with constant thickness and elasticity, the displacement, strain and stress vary substantially as a function of the position on the wall. Similarly, in our CFD simulations we found that the local blood flow velocity varies significantly as a function of the position in the lumen. Our initial simulations are not yet completely patient-specific. Further effort will be needed to accurately segment thrombus, wall and calcifications, to determine the patient-specific material properties of each of these components and to develop a method for the assessment of the blood pressure at the input or output of the AAA (one of the boundary conditions for the CFD simulations).

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Rerefences

[1] O. Gerard et al., "Efficient Model-Based Quantification of Left Ventricular Function in 3-D Echocardiography", IEEE Trans. on Medical Imaging, Vol. 21, No. 9, September 2001, pp. 1059-1068.

[2] S. Lobregt and M.A. Viergever, "A Discrete Dynamic Contour Model", IEEE Trans. on Medical Imaging, Vol. 14, No. 1, March 1995, pp. 12-24.

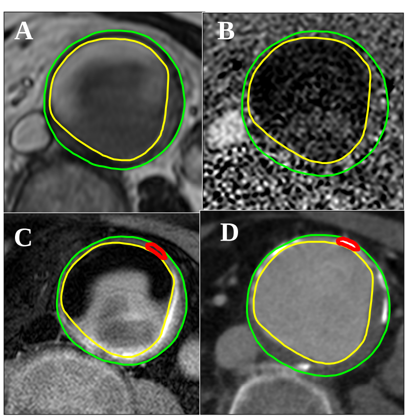

Figure 1 – One slice through an 58-mm AAA: a) 3D Balanced TFE MRI, b) Quantitative Flow MRI, c) 2D TSE Black Blood MRI, d) CT Angiography. Images a, b and c were acquired on a Philips Medical Systems (PMS) Intera Rel. 9 and image d on a PMS AVEU CT scanner. Green: outer wall, yellow: lumen boundary, red: example of calcification.

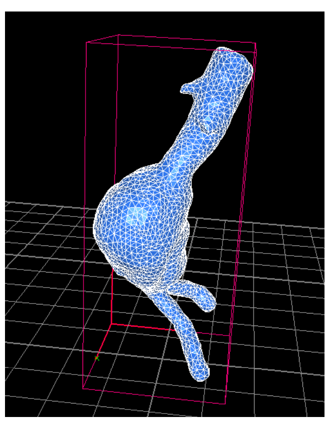

Figure 2 – Example of the result of a 3DAO-based segmentation of the lumen of an AAA (represented as a surface triangulation).

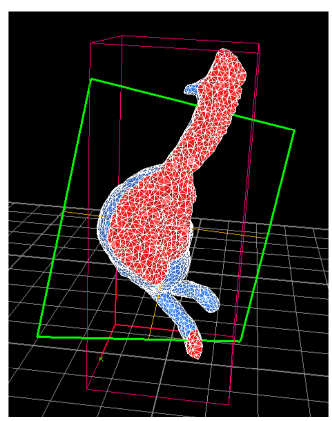

Figure 3 – Cut-plane through the result of the tetrahedral volume meshing based on the surface triangulation of figure 2.

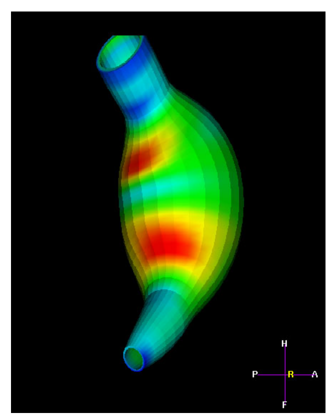

Figure 4 – Computed wall stress shown as colour overlay on the 3D hexahedral wall mesh (colour scale ranging from blue=low to red=high stress). Only one of the branches of the bifurcation into the legs is shown.