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

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Abstract

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 have therefore started to investigate if better rupture risk indicators can be obtained by patient-specific hemodynamic modeling. This paper presents our initial results for each of the steps involved in this modeling. We found that the simulated wall stress varies significantly as a function of the position on the AAA wall, which suggests that the AAA geometry itself may play an important role in rupture.

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1 - Introduction

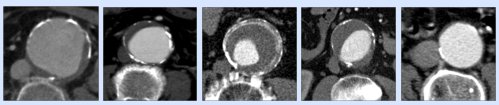
An abdominal aortic aneurysm (AAA) is a life-threatening dilatation of the abdominal aorta. Rupture of an AAA leads to death in the majority of cases. At present, surgical treatment is usually decided if the AAA diameter exceeds 5 cm, but rupture does occur for smaller diameters. The patient-specific hemodynamics may play a role in this rupture. We have therefore started to investigate if parameters obtained by patient-specific hemodynamic modeling can better predict the risk of AAA rupture.

2 - Methods and Materials

Hemodynamic modeling of an AAA involves a number of steps, which are briefly described in this section.

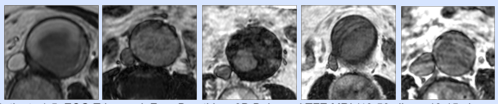
AAA imaging

Conventionally, single-slice 3D CT Angiography (CTA) is used to visualize the lumen, thrombus and calcifications of an AAA:

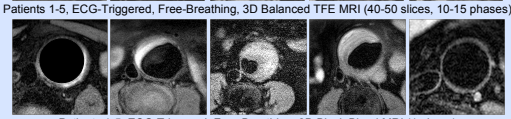


Patients 1-5, Catharina Hospital Eindhoven, The Netherlands (PMS AVEU CT scanner)

CTA does however not supply information about the time-varying geometry of the aorta wall. We consider wall information to be essential for rupture risk prediction and have therefore developed specific ECG-triggered MRI protocols for imaging of the lumen, thrombus and wall (PMS Intera 1.5T scanner):



Patients 1-5, ECG-Triggered, Free-Breathing, 3D Balanced TFE MRI (40-50 slices, 10-15 phases)

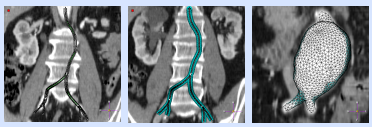


Patients 1-5, ECG-Triggered, Free-Breathing, 2D Black Blood MRI (1 phase)

2

Segmentation

For the segmentation of the various AAA components we are investigating the technique of 3D Active Objects (3DAO). First the lumen centerline is automatically detected and a tubular-shaped initial 3DAO is placed around the centerline. This tube-shaped 3DAO is then automatically deformed until it reaches the boundary of the object to be segmented. Example for lumen segmentation from CTA:

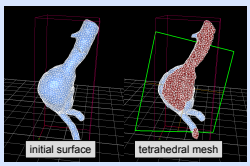


lumen centerline | tube around the centerline | surface resulting from 3DAO segmentation

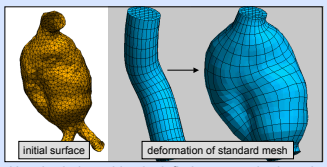
Volume meshing

The 3DAO segmentation results in a triangulated surface description, which has to be translated to a volume mesh. We are comparing two approaches:

- a local Delaunay tetrahedral meshing algorithm with control over the resolution and quality of the generated tetrahedrons (Philips Research France).
- a hexahedral meshing algorithm that deforms a standard mesh to the surface resulting from the segmentation (Technical University Eindhoven).



Delaunay tetrahedral meshing



Hexahedral meshing by inflating a standard mesh

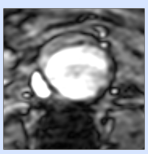
Formulation of the discrete hemodynamic equations

For our flow simulations we have used the Navier-Stokes equations. In our wall-motion simulations we have assumed linear elastic wall behaviour.

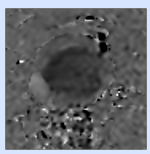
3

Boundary conditions and material properties

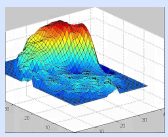
The blood flow at the input and the output of the AAA, the boundary conditions needed for the flow simulation, can be measured with quantitative flow MRI (Qflow):



Qflow amplitude



Qflow phase



flow measurement

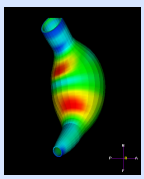
So far, we have used normal instead of patient-specific values for the blood pressure and the material properties (blood viscosity, wall elastics).

Finite-element solving

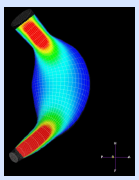
Our flow and wall-motion simulations were performed with the Sepran finite-element modeling package (Technical University Delft, The Netherlands).

Visualization of results

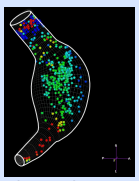
Intuitive visualization of the large amount of simulation data is of great importance for the interpretation of these data by the user of our simulation packages. We have therefore developed dedicated visualization software. Some examples:



colour overlay of wall stress



cut plane with colour-coded flow velocity



1 frame of particle flow movie

4

3 – Results

AAA imaging

3D BTFE MRI clearly visualizes wall motion, but does not discriminate lumen and thrombus as well as CTA. Quantitative flow MRI is well suited for the quantification of blood flow velocity. Black-Blood MRI can be used for the visualization of the aorta wall and the presence of thrombus and even shows significant anatomical detail inside the thrombus. Calcifications are very clearly visualized by CTA, whereas they are hardly visible in the MR images.

Segmentation

The technique of 3DAO is well suited for lumen segmentation. Optimization of 3DAO-based thrombus segmentation is ongoing and first results look promising as well.

Hemodynamic simulations

In our wall-motion simulations we found that, even though the models are yet far from patient specific, the wall displacement, strain and stress vary substantially as function of the position on the wall. Furthermore, in our flow simulations we found that the velocity distribution in the AAA can vary significantly from that in healthy abdominal aortas.

4 – Conclusions

The combination of CTA and MRI is needed for the complete geometrical modeling of all AAA components (lumen, thrombus, wall, calcifications).

Our wall-motion simulations show that the wall stress varies significantly as a function of the position on the AAA wall. This suggests that the AAA geometry itself may play a role in rupture.

Our simulations are still far from patient-specific. The next step will be the inclusion of the patient-specific thrombus and wall with calcifications and the use of more realistic wall models and patient-specific material properties.

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