MR-BASED IMAGING FOR PATIENT SPECIFIC, FULLY COUPLED 2-WAY FLUID-STRUCTURE INTERACTION OF THE HUMAN AORTA

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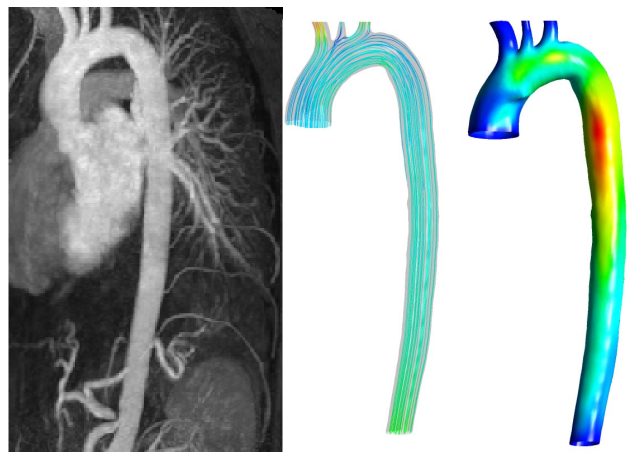
Introduction

Wall shear stress is well established as an indicator of increased risk for development of atherosclerotic plaques, platelet activation and thrombus formation. Predicting the sites of wall shear stresses that are deemed dangerous before intervention would be of great aid to the surgeon. However, the geometries used for these kinds of simulations are usually considered rigid, but to more accurately capture the flow (and solid) dynamics of a realistic human aorta, fluid-structure interaction (FSI), which allows movement of the wall, is needed. The pressure wave and its effect on the wall motion are resolved and enable a more physiological model as compared to the rigid wall case. FSI is an iterative process where the fluid pressure is taken as an input to the solid solver that calculates a displacement which is then fed back to the fluid solver as an updated geometry. Here we propose a method to accurately compute the wall shear stress on the entire aortic wall, using MRI data to construct patient specific geometries with measured flow velocities in the simulations.

Method

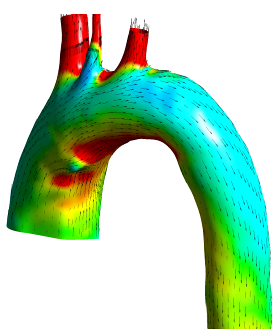
Geometrical as well as flow data were acquired using a 1.5 T Philips Achieva MRI scanner. The complete aorta was obtained within a breath hold and the 3D volume data was reconstructed to a resolution of 0.78x0.78x1.00 mm^3. To retrieve physiological inlet velocities for the fluid simulation, time-resolved aortic flow velocities were obtained by performing throughplane 2D velocity MRI acquisition placed supracoronary and perpendicular to the flow direction and was reconstructed to 40 time-frames per cardiac cycle with a spatial resolution of 1.37x1.37 mm^2.



Left: MRI MIP representation of the geometry
Middle: blood flow streamlines
Right: aortic wall colored with displacement

To extract aortic geometry from MRI images a 3D level set algorithm was used for segmentation. In the image-volume one or several seed points/regions are defined and an implicit surface was allowed to expand out-wards to the edge of the object. The algorithm was implemented into a cardiac image analysis software package [1]. The segmentation software gives a STL-representation of the inner aortic wall which is used for the fluid simulation. For the aortic wall a thickness distribution was assumed and applied to the geometry, and subsequently used in the aortic wall simulation.

High quality hexahedral computational meshes were constructed and used for both the fluid and the solid geometries. In the solid domain a non-linear hyperelastic wall model was used, with material parameters based on biological stress-strain measurements found in literature, e.g. [2]. To get a realistic pressure outlet condition on the fluid domain, the pressure at the four outlets was computed with windkessel models, which describes the relationship between the aortic outflow and aortic pressure. The outflow windkessel models are capable of defining physiologically relevant pressure waves at the outlets which includes reflections from branches and arteries distally to the analyzed arterial segment.



Aortic arch colored with wall shear stress and velocity vectors

Discussion

The method demonstrates the possibilities of coupling FSI with MRI data, and initial results look very promising. Segmentation and simulation setup can be done fairly automated, but creation of the computational meshes still needs to be further developed and automated to minimize the time from MRI acquisition to finished simulation. Presently, FSI is very computationally expensive and requires computer power that is well above a normal desktop PC. Feasibility of the proposed method is shown by this work, which incorporates MRI data into highly advanced simulations to retrieve a more physiologically correct estimation of wall shear stress.

References

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[2] J. Stålhand, Determination of human arterial wall parameters from clinical data, 2009, Biomech Model Mechanobiol 8:141–148