Flow Sensitive MRI in a Realistic Model System of the Thoracic Aorta with Aortic Coarctation.

R. Lorenz[1], A. F. Stalder[1], J. Bock[1], D. Klausmann[2], C. Benk[3], J. Hennig[1], and M. Markl[1]

[1]Dept. of Diagnostic Radiology - Medical Physics, University Hospital Freiburg, Freiburg, Germany, [2]IMTEK, University Freiburg, Freiburg, Germany, [3]Dept. of Cardiovascular Surgery, University Hospital Freiburg, Freiburg, Germany

Introduction: For the diagnosis and treatment of aortic diseases, flow sensitive MRI has been used to assess normal and pathological blood flow characteristics [1-3]. Although in-vivo studies are ideal, they do not offer the possibility to predict changes of hemodynamics effects due to vascular modifications. Realistic in-vitro vascular phantoms in combination with MRI flow measurements provide a useful tool for the modeling of different stages of vascular diseases and their effect on blood flow dynamics [4]. The aim of this study was to establish a realistic in-vitro vessel model system of the thoracic aorta produced by rapid prototyping (RP) [5]. The RP model was used for the evaluation of severity and progression of aortic coarctation, i.e. a common aortic pathology resulting in luminal narrowing in the distal descending aorta. Additionally a novel approach to generate realistic in-flow waveforms was implemented by using a MR-compatible pneumatically driven ventricular assistant device (VAD). The VAD pump-system, clinically used for the cardiovascular support of heart failure patients, permits the generation of pulsatile flow comparable to real in-vivo conditions.

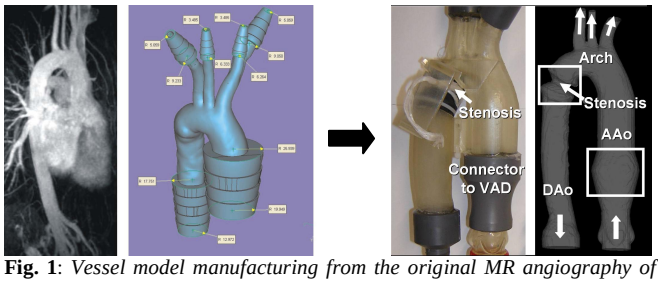

Fig. 1: *Vessel model manufacturing from the original MR angiography of the aorta (left) and a computer model including added connection adapters (mid). Right: Final RP vessel model with connector to the VAD in the ascending aorta (AAo) and the integrated stenosis in the descending aorta (DAo) and the corresponding isosurface derived from MRI measurements.*

Material and Methods: Rapid prototyping (Polyjet Eden 330, Objet Geometries Ltd., Israel) was used to transform a normal aortic MR angiography into a realistic vascular model of the thoracic aorta (Fig. 1) [5]. Aortic coarctation with different stenosis grades was modeled by replacing the RP model wall with a bicycle inner tube into the distal descending aorta. Figure 2 illustrates the set up of the MR-compatible flow cycle in the MR-scanner with the VAD (chamber size = 54 ccm, MEDOS Medizintechnik AG, Germany) attached to the ascending aorta of the RP model. The pump and control unit outside the MR room was connected by long tubes (~ 8 meters) to the VAD to transfer periodic pressure waveforms to the flow circuit (P_{sys}: 100-140 mmHg, P_{dias}: 60-90 mmHg). All experiments were performed on a 3T MR system (TRIO, Siemens, Germany) using time resolved phase contrast MRI with three-directional velocity encoding (flow sensitive 4D MRI) [6]. A program written in LabView® (National Instruments, USA) and a multi functional data acquisition board (DAQ) (USB 6008, 12bit, 10 kS/s) were used to provide an ECG-trigger for the VAD pump-unit and for gating the flow sensitive 4D MRI measurements. Imaging parameters were: velocity sensitivity = 150cm/s, temporal resolution: 41.6 ms, time frames: 17, spatial resolution = 2.29×1.25×1.8 mm^3, FOV = 220×320 mm^2, slices: 36, flip angle = 15°, TE: 2.7 ms, TR: 5.2 ms. 3D visualization (EnSight, CEI, NC, USA) was used to evaluate 3D flow characteristics for five different stenosis grades. Further, a home built tool (Matlab, The Mathworks, USA) was used for lumen contour segmentation and flow velocity quantification in 14 slices distributed along the RP model (Fig. 3, left)

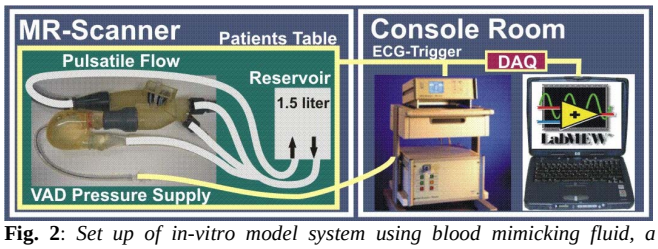

Fig. 2: *Set up of in-vitro model system using blood mimicking fluid, a pneumatically driven VAD pump and ECG- triggering via LabView.*

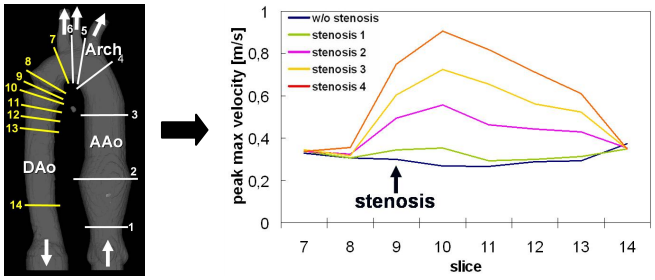

Fig. 3: *Peak velocities for different stenosis grades in the descending aorta for slices 7 to 14. The highest peak max velocities are found in slice 10 immediately after the stenosis. In the subsequent post-stenotic slices peak max velocities decrease to similar velocities for all experiments in slice 14.*

Results: In-vitro 3D flow analysis using the aortic RP model integrated in a pulsatile flow cycle driven by a VAD pump-system were successfully performed for five different stenosis grades. 3D stream-line visualization was used to characterize the changes of flow patterns for different stenosis grades as shown in figure 4. Higher grade stenosis revealed expected increased velocities and additionally changes of flow pattern in the stenotic region during peak systole (small arrows, time frame 11). With increasing stenosis grade, more pronounced and accelerated jet flow directed towards the vessel wall are clearly indicated by the streamlines. Detailed quantitative flow analysis (Fig. 3) demonstrated an increase of peak velocities of up to 200%. Additionally, a considerable increase in helical flow distal to the stenosis for increasing coarctation grade was observed (small arrows, time frame 13). Moreover, with increasing stenosis grade velocities increased at the supraaortal branches and enhanced vortex flow was found at the inlet of the aortic vessel model.

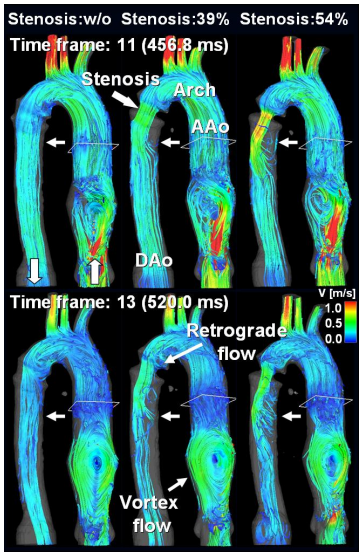

Fig. 4: 3D *Stream-lines for two time frames and different three stenosis grades. Marked increased velocities and changes in flow patterns such as helical flow for higher grade stenosis in the post-stenotic descending aorta are evident.*

Discussion: Experimental simulation and analysis of 3D flow patterns in normal and pathological in-vitro models has the potential to evaluate functional consequences of alterations of disease. Our findings indicate that progressing coarctation results in expected flow changes at the site of the pathology but can also affect the entire thoracic aorta. Marked increase in helical flow in the descending aorta or enhanced vortex flow in the ascending aorta, indicate that local pathological changes may affect more distant regions and may result in the development of secondary pathologies due to altered flow or wall parameters. The results of the study proved that the pneumatic VAD pump system could be used in combination with in-vitro flow analysis based on a small flow cycle in the MR system. Such setups may result in reduced distortions of pulsatile waveforms compared to positive displacement pumps for which long fluid containing tubes are needed to connect pump and phantom. Note that the connection and the transition of the VAD to the in-vitro vessel model resulted in an enlargement in vessel diameter causing strong vortex flow at the inlet. Further, the design of the stenosis created retrograde flow in the pre-stenotic region. Optimizations of the existing vessel model such as the enlarged vessel diameter, stenosis design and stiff vessel walls are essential for further investigations.

Acknowledgements: Grant support by the Deutsche Forschungsgemeinschaft (DFG), Grant # MA 2383/4-1 and the Bundesministerium für Bildung und Forschung (BMBF), Grant # 01EV0706.

References: 1. Bammer, R., et al., MRM, 2007. **57**(1): p. 127-40. 2. Chai, P., et al., JCMR, 2005. **7**(4): p. 705-16. 3. Wigstrom, L., et al., MRM, 1999. **41**(4): p. 793-9. 4. Canstein, C., et al., MRM, 2007, in press. 5. Markl, M., et al., Magma, 2005. **18**(6): p. 288-92. 6. Markl, M., et al., JMRI, 2003. **17**(4): p. 499-506.