Time-resolved 3D MR Velocity Mapping in a Realistic Vascular Rapid-Prototyping Model of the Thoracic Aorta

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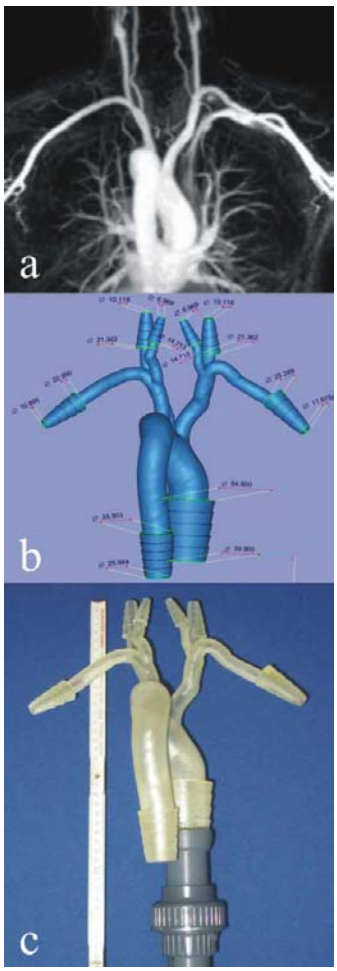
Introduction: State-of-the-art rapid prototyping technology permits the creation of an exact one-to-one replica of any geometrical structure derived from 3D computer models. Previously reported studies have proven that in-vitro models generated by rapid prototyping are MR-compatible and can be used in combination with in-vitro flow simulations for phase contrast MRI in a standard clinical MR system [1, 2]. As a result, exact replicas of vascular geometries of individual patients have the potential to serve as flow phantoms and provide insight into local flow characteristics and vascular hemodynamics. In this study rapid prototyping was successfully used to convert a vascular geometry of the entire thoracic aorta as measured by contrast enhanced MR-Angiography (CE-MRA) into a realistic flow phantom with large anatomical coverage and high spatial resolution. Integration into a flow circuit with patient specific pulsatile flow and application of time-resolved 3D MR velocity mapping permitted detail analysis of local and global flow dynamics in a realistic patient-specific environment [3].

Methods: All experiments were performed on a 3T MR-system (TRIO, Siemens, Germany). CE-MRA data (figure a) from a patient with normal aortic geometry (0.1 mmol/kg dose at 2 ml/s, 20 second breath-hold, TE/TR=1.16ms/2.84ms, spatial resolution=(0.8x1.2x1.4)mm³) were segmented to create a 3D computer-model of the vascular lumen using region growing algorithms and manual editing (software: MIMICS and MAGICS RP, Materialise, Belgium). Following conversion into a 3D surface mesh structure constant thickness vessel walls and hose-connection adaptors were added (figure b). The resulting model was transformed into a real-size flow phantom using state-of-the-art rapid prototyping technology (Polyjet Eden 330, Objet Geometries Ltd., Israel) and connected to an MR-compatible pump system (CardioFlow 1000 MR, Shelley Medical Imaging Technologies, Canada) via PVC-hosing. Flow experiments were performed with blood-mimicking fluid (60% distilled water and 40% glycerol, representative of the viscosity of blood) doped with contrast agent (Magnevist, Schering, Germany) with an empirically determined concentration of 1.08 mmol/l to optimize signal to noise ratio. In order to generate realistic pulsatile inflow, the flow waveform in the proximal ascending aorta was measured in the same patient using 2D phase contrast MRI (α=15°, TR=5.3ms, temporal resolution=23.2ms, venc=1m/s and spatial resolution=(1.43x2.00x8.00) mm³). Based on the temporal evolution of mean velocities, the pump system was programmed to reproduce this waveform (mean flow: 65.7 ml/s, period: 768 ms). Time-resolved 3D MR velocity mapping using a 8 channel phase array body coil and an rf-spoiled gradient echo sequence with interleaved 3-directional velocity encoding was applied to access resulting 3D flow characteristics within the rapid prototyping model (BW=+/-480 Hz/pixel, α=15°, TR=6.1ms, temporal resolution=48.8ms, venc=1.5m/s, spatial resolution =(2.00x1.56 x3.20)mm³)[3]. Measurements were prospectively gated to the ECG cycle simulated by the pump system. After magnitude mask filtering computer aided advanced 3D flow visualization of the time-resolved 3D flow phantom data was performed (EnSight, CEI, NC, USA) and included 3D velocity vector fields, 3D streamlines and 3D particle traces (time-resolved path of virtual particles over the entire cardiac cycle) which arise from the grid points of a 2D emitter plane that could be positioned at any location inside the 3D imaging volume.

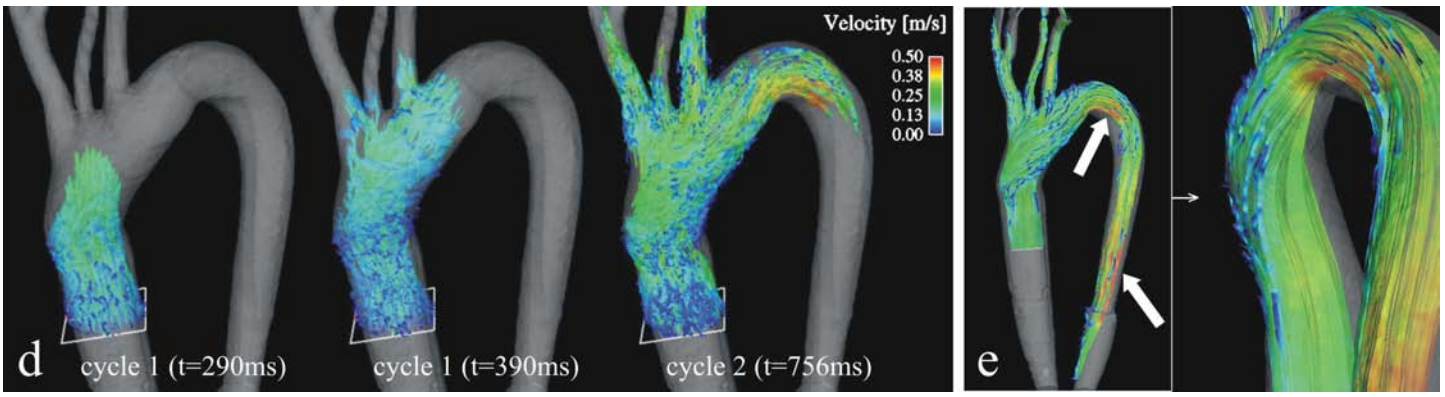
Results: Flow experiments and time-resolved phase contrast velocity mapping measurements were successfully performed inside a flow model of a realistic vascular geometry produced from CE-MRA using rapid prototyping technology. 3D visualisation was applied to the data in order to identify characteristic flow patterns from the immense set of measured information. The three time phases in figure d are an example of a 3D particle trace visualisation demonstrating the filling of the supra-aortic branches in two cycles and an accelerated passage through the aortic arch. 3D stream-line visualisation in figure e shows a slight right-handed helical outflow in the ascending aorta and areas of accelerated flow in the aortic arch and the descending aorta (arrows). All findings are in agreement with previously reported aortic blood flow patterns in normal volunteers [4]. Comparison of inflow characteristics measured in the phantom with blood flow velocities measured in the patient indicated a variation of the initial waveform produced by the pump during propagation through the hosing.

Discussion: The results of this study illustrate that rapid prototyping in combination with MR angiography and 3D velocity mapping could successfully be used to analyse local and global flow dynamics in a realistic one-to-one replica of a patient's thoracic aortic anatomy. When used as in-vitro flow phantoms, rapid prototyping models may help to understand the blood flow characteristics associated with a given vascular pathology. Discrepancies of blood flow patterns in patients and in the flow model may arise from simplified experimental conditions such as stiff model walls and modified in-flow conditions. Further studies are therefore planned to understand the waveform variation of the propagating wave to permit a more precise generation of realistic in-flow conditions. In addition, flow conditions are to be reconstructed more realistic by using higher cardiac output rates and elastic wall flow models. Future projects include comparisons of the measured 3D velocity fields with patient flow data and with numerically simulated flow (computational fluid dynamics, CFD) in the same geometry [5, 6]. The aim is to verify these flow simulations that could assist in the evaluation and planning of surgical interventions.

References: [1] Chong, et al; Proc Inst Mech Eng [H] 1999; 213:1-4. [2] Elkins, et al; Experiments in Fluids 2003; 34(4): 494-503. [3] Markl, et al; J Magn Reson Imaging 2003; 17(4):499-506. [4] Bogren, et al; J Magn Reson Imaging 2004; 19:417-427. [5] Holton, et al; J Magn Reson Imaging 2005; 22:248-257. [6] Long, et al; Magn Reson Med 2000; 43:565-576



Figures a-c) flow model generation:
a) CE-MRA
b) segmented computer-model
c) rapid prototyping flow model



Figures d-e) 3D visualisations:
d) 3D particle traces at three different phases demonstrating the filling of the aortic arch in two cycles
e) Systolic 3D stream-line visualisation (t=170.8ms) clearly shows areas of high flow (arrows) and helical outflow in the ascending aorta