3D MR Flow Analysis in a Realistic Rapid-Prototyping Model System of the Thoracic Aorta: Comparison with in-vivo Data and Computational Fluid Dynamics in Identical Vessel Geometries

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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 conducted studies have proven that such models are MR-compatible and can be used in combination with in-vitro flow simulations for phase contrast MRI in a standard clinical MR system [1-3]. The purpose of this study was to test the feasibility of patient-specific vascular rapid prototyping model systems in combination with flow sensitive 4D MRI measurements [4]. Direct comparison with results from in-vivo measurements and numerical simulation (computational fluid dynamics, CFD) in identical vessel geometries of the human thoracic aorta indicate the potential of such patient specific model systems for the validation of CFD studies and detailed simulation of realistic vascular hemodynamics [5].

Methods: All experiments were performed on a 3T TRIO system (Siemens, Germany).
Rapid Prototyping Models: Contrast enhanced MR angiography (CE-MRA) of the thoracic aorta was performed in 3 patients with pathological (n=1) and normal (n=2) aortic geometry (spatial resolution=(0.8 x 1.2-1.5 x 1.3-1.4)mm³). All CE-MRA data sets 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). Next, state-of-the-art rapid prototyping technology (Polyjet Eden 330, Objet Geometries Ltd., Israel) was applied to transform the computer models into real size vascular replicas (figure 1A).
In-vitro Model System: Two models were used as patient specific flow phantoms and connected to an MR-compatible pulsatile flow circuit including a reservoir, a pressure control valve, and a MR compatible computer controlled pump system. Realistic pulsatile in-flow conditions were extracted from in-vivo 2D CINE phase contrast (PC) MRI normal to the ascending aorta (venc=150cm/s, temp. resolution=42.4ms). Matched in-flow waveforms at the inlet of the vascular model were generated using the flow pump (figure 1B).
In-vitro 3D Flow Analysis: Flow measurements covering the entire vascular model were performed using time-resolved 3D PC MRI (flow sensitive 4d-MRI) with interleaved 3-directional velocity encoding (spatial resolution of = 2.00 × 1.56 × 3.20 mm³, α =15°, TE/TR=3,7/6,1ms, venc=150cm/s, temporal resolution = 48.8 ms). Measurements were prospectively gated to the ECG cycle simulated by the pump system.
In-vivo & in-vitro 3D Flow Analysis: For comparison flow sensitive 4d-MRI of the entire thoracic aorta was performed in one patient with somewhat reduced spatial resolution of 2.39 × 1.56 × 3.00 mm³. Navigator gating enabled free breathing during data acquisition.
CFD: Based on the 3D CE-MRA a 3D Finite Element (FE) mesh structure was generated to define the vascular geometry for the CFD simulations. To ensure closely matched boundary conditions, the in-flow waveform was extracted from the flow-sensitive 4D MRI dataset as of the vascular model. Pulsatile 3D flow within the aortic geometry was calculated using a commercially available FE-program (ADINA, MA, USA). All calculations were based on a Navier-Stokes model, assuming a Newtonian fluid and laminar flow.

Results: Rapid prototyping was successfully used to convert 3 vascular geometries of the entire thoracic aorta into realistic vascular replicas. Integration into a flow circuit with patient specific pulsatile flow and application of flow sensitive 4D MRI permitted detailed analysis of local and global flow dynamics in a realistic patient-specific environment. 3D blood flow visualisations for model and patient generally revealed similar flow patterns. For the in-vivo data, however, higher velocities and more effective filling, especially of the supra-aortic branches were observed (figure 2). Detailed quantitative comparisons between in-vivo, in-vitro and CFD results were performed in 9 slices distributed along the thoracic aorta. As an example, figure 3 illustrates a detailed comparison of pulsatile mean velocities over the cardiac cycle in six out of nine slices for all three modalities. Excellent agreement between in-vitro measurements and CFD is clearly visible which is also supported by linear correlation analysis of mean velocities in all slices and time frames (linear fit, slop = 0.81, intercept = 0.07 r^2 = 0.94). Somewhat reduced agreement with generally lower velocities in the vascular model was found for the in-vivo vs. in-vitro comparison (linear fit, slope =, 0.61 intercept = 0.01 r^2 = 0.93) probably caused by insufficient pump performance.

Discussion: Initial results illustrate that rapid prototyping in combination with MR angiography and 3D velocity mapping could successfully be used to analyze local and global flow dynamics in realistic model systems. Comparison with true in-vivo flow patterns measured in the same patient and with numerical flow simulations (CFD) are highly promising. However, additional direct comparisons of local flow profiles need to be performed to correctly identify the limitations of CFD and in-vitro modelling of vascular hemodynamics. Future studies are thus needed to refine the model system and include additional components of the cardiovascular system such as valves and pulsating ventricular chambers. Once established, cardiovascular in-vitro model systems offer the opportunity to modify size and shape of the pathology (e.g. stenosis grade, aneurysm size) to model and study the influence of the progression of the disease or even to simulate hemodynamic consequences of surgical intervention (e.g. mechanical versus biological prosthetic valves).

References: 1. Chong CK, et al; Proc Inst Mech Eng [H] 1999; 213:1-4. 1. **2.** Markl M, et al. Magma 2005;18(6):288-292. **3.** Elkins CJ, et al; Experiments in Fluids 2003; 34(4):494-503. **4.** Markl M, et al J Comput Assist Tomogr 2004;28(4):459-468. **5.** KL Leea, Doorly DJ, Firmin, DN. Medical Physics, 33(7) 2621-2631

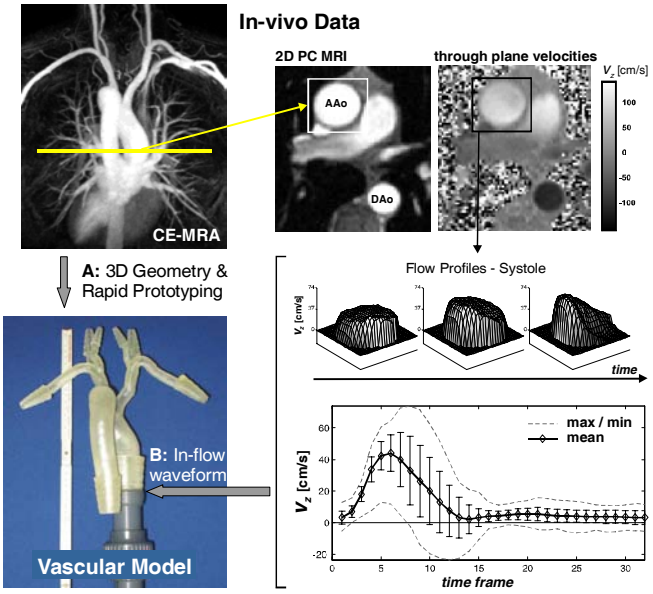

Fig. 1: **A:** 3D CE-MRA data of a normal thoracic aorta was used to generate a 3D computer model including connection adapters which was then converted in a real physical replica using rapid prototyping technology. **B:** To establish a realistic in-vitro model system, the replica was integrated into a pulsatile flow circuit with in-flow boundary conditions measured in the same patient using 2D CINE PC MRI.

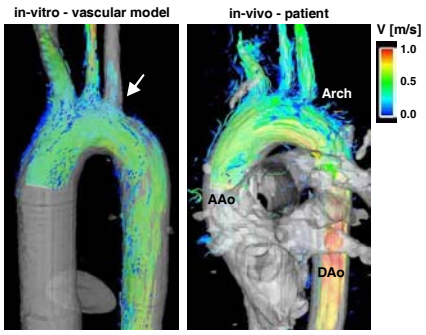

Fig.2: Particle traces representing systolic 3D blood flow as measured by flow-sensitive 4D MRI in-vivo (right) and in the vascular model with matched geometric and in-flow boundary conditions. More effective filling of the supra-aortic branches and higher velocities are visible for the patient.

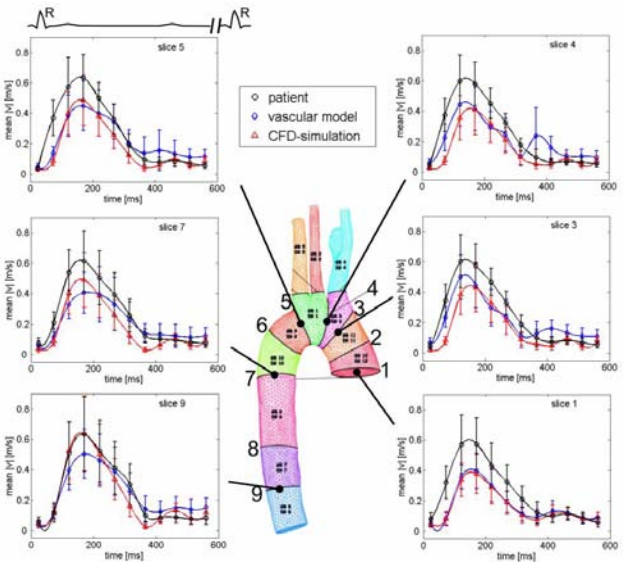

Fig. 3: Comparisons of the flow curves for patient, vascular model and CFD-simulations (mean velocities over time).