Improved simulation of 3D flow characteristics in a pressure controlled in vitro model system

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Introduction: It is well known that altered vascular hemodynamics is related to the development of life threatening vascular diseases such atherosclerosis or aneurysms [1,2]. However, the direct link between flow pattern changes and their effect on the progression of pathology is often not fully understood. In this context, in-vitro model systems provide a useful tool for the systematic evaluation of hemodynamic changes associated with geometric vascular modifications. Recently, realistic vascular in-vitro phantoms in combination with a pulsatile flow circuit and 4D MRI flow measurements were used to evaluate their utility to reproduce realistic in-vivo hemodynamics [3]. Similar setups using a MR-compatible pulsatile pump chamber were used to model different vascular deformations and evaluate their effect on blood flow dynamics [4,5]. However, it remains difficult to accurately model in flow boundary conditions and 3D flow characteristics while maintaining physiological pressures within the circulation system. In this study, a novel in-vitro model setup (system 2) is presented which permits flexible pressure control using an adjustable mock loop to simulate physiological pre- and afterload conditions. Realistic in-flow conditions were generated by a MR-compatible pneumatically driven ventricular assist device (VAD), a pump chamber including valve regulated in and out flow. The resulting flow data were compared to in-vivo 3D flow characteristics and to in-vitro model systems without pressure control (system 1). A one to one replica of a normal aorta and an aorta with ascending aortic aneurysm were generated by rapid prototyping [6].

Material and Methods: Figure 1 illustrates the setup of the MR-compatible flow cycle for the in vitro model and integrated mock loop in the MR-scanner and the pump and control unit (MEDOS Medizintechnik AG, Germany), external ECG trigger and real-time MR-compatible pressure monitoring outside the MR room. For system 2, real-time pressure monitoring, liquid filled catheters were connected to the inlet and outlet of the in-vitro models. Pressure adaption to in vivo conditions was performed using individually adjusted water levels and valve settings in the mock loop prior to each measurement. Additionally VAD pump performance was improved for optimal filling and emptying of the pump chamber. Blood mimicking fluid was used as blood substitute and additionally contrast agent was added to increase SNR. All experiments were performed on a 3T MR system (TRIO, Siemens, Germany) using a time resolved phase contrast MRI pulse sequence with three-directional velocity encoding. 3D visualization (EnSight, CEI, NC, USA) was employed to compare in-vivo and in-vitro 3D flow characteristics. A home built tool (Matlab, The Mathworks, USA) was used for lumen contour segmentation and flow velocity quantification in 3 slices distributed along the aorta (figure2 and 3).

	in-vivo	system 1	system 2
velocity enc.:	200 / 150 cm/s	150 / 100 cm/s	150 / 100 cm/s
temp. res.:	48.8 / 48.8 ms	42.4 / 41.6 ms	40.8 / 41.6 ms
spat. res.:	2.4×1.6×3.0mm^3 / 2.9×1.7×3.5mm^3	1.5×1.2×1.8mm^3 / 2.3×2.3×2.0mm^3	2.0×1.7×2.2mm^3 / 2.0×1.7×2.2mm^3

Table 1: Imaging parameter for the normal aorta / aneurysm patient and the corresponding in-vitro model systems 1 and 2.

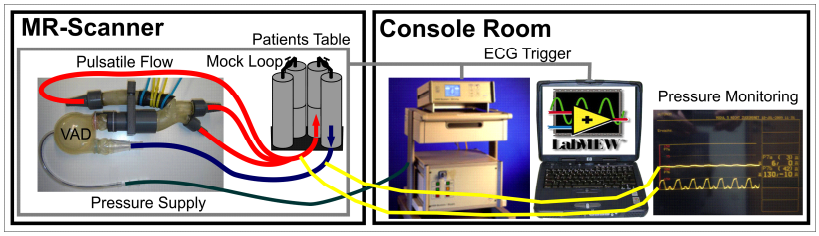

Figure 1: Experimental setup with in-vitro model and VAD mimicking the left heart directly attached to the vessel model and integrated mock loop for physiological pressure adjustments in the MR scanner room and pump unit, external ECG trigger and pressure monitoring outside the MR-scanner.

Results: The new in-vitro flow simulation setup was successfully used to generate systolic pressures at the outlet of the model systems of 128 mmHg for the normal aorta and 125 mmHg for the aneurysm model closely resembling typical in-vivo conditions. On-line monitoring of pulsatile pressure changes, as illustrated in figure 1, demonstrated stable and flexible adjustable pressure conditions throughout the experiments. In contrast to measurements without pressure control and optimised pump performance of the VAD, an improved generation of qualitative and quantitative flow characteristics compared to in-vivo flow conditions could be achieved (figure 2 and figure 3).

Discussion: The setup with physiological pressure simulation provided pulsatile flow comparable to in vivo conditions. Additional pressure monitoring allowed for controlled physiological pressure adaption to in vivo conditions. Optimized VAD pump performance led to notably improved velocities for the normal aorta and the aneurysm model.

Acknowledgements:

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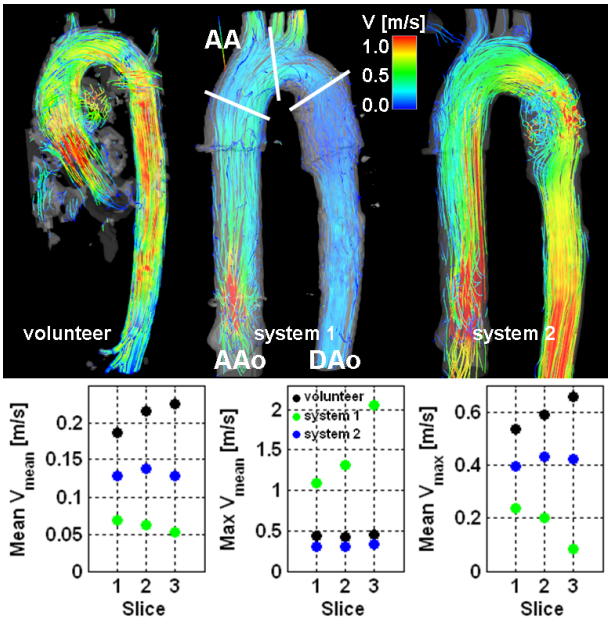

Figure 2: Comparison of peak systolic 3D streamlines of a normal aorta (in vivo) and corresponding in-vitro models without pressure control (system 1) and with controlled adjustment of pressure conditions at in- and outlet (system 2). System 2 (blue circles) shows more closely matching mean and peak velocities compared to in vivo results (black circles).

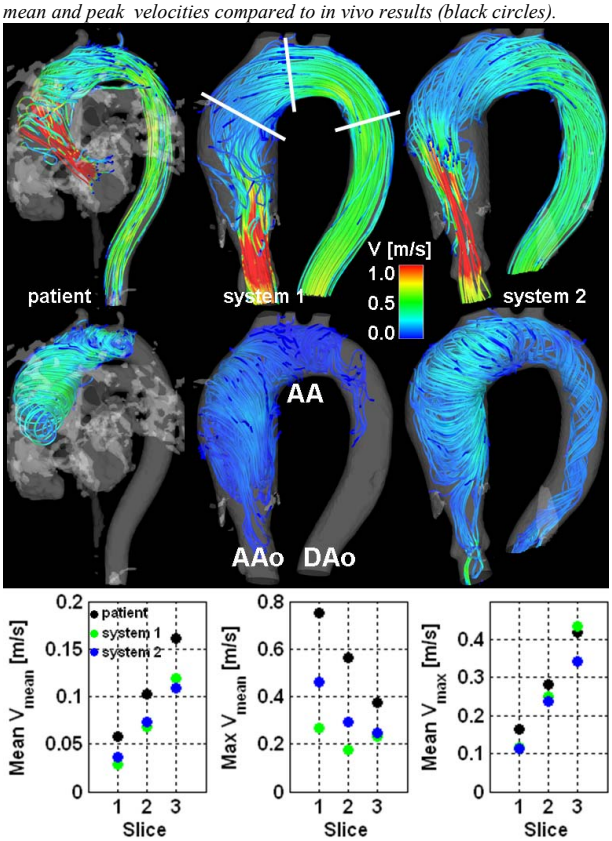

Figure 3: Comparison of peak systolic (top) and diastolic (bottom) 3D streamlines in a patient with an ascending aortic aneurysm (in vivo) and corresponding in-vitro models without pressure control (system 1) and with pressure control (system 2). In addition to a mild improvement in velocities, the boundary conditions in system 2 provided an improved generation of the distinct aneurismal vortical flow patterns as seen in-vivo.