4D MRI Flow Analysis in an in-Vitro System Modelling Continuous Left Ventricular Support: Effect of Cannula Position in the Thoracic Aorta

Christoph Benk[1], Alexander Mauch[1], Friedhelm Beyersdorf[1], Rolf Klemm[1], Jan Korvink[2], Michael Markl[3], and Bernd A Jung[4]

[1]Dept. of Cardiovascular Surgery, University Medical Center, Freiburg, Germany, [2]IMTEK – Department of Microsystems Engineering, Laboratory for Simulation, Albert-Ludwigs University, Freiburg, Germany, [3]Dept. of Radiology, Feinberg School of Medicine, Northwestern University, Chicago, Illinois, United States, [4]Dept. of Radiology, Medical Physics, University Medical Center, Freiburg, Germany

Target audience: Clinicians working in Cardiovascular surgery or Cardiology.

Purpose: Continuous blood flow from left ventricular assist devices (LVAD) through cannulaes anastomosed to the ascending or descending aorta has become an important treatment option for heart failure patients waiting for heart transplantation or to provide a (long term) support for the failing heart [1]. However, recent reports indicate that complex geometric alterations of the cardiovascular system associated with device implantation as well as the introduction of constant flow into the vascular system may alter blood flow patterns in the native aorta, potentially affecting perfusion patterns to the supra-aortic vasculature or causing structural changes to the aortic root leading to aortic regurgitation, valve dysfunction or thrombus formation [2]. The purpose of this study was to employ 4D flow MRI for the investigation of blood flow alterations in an in-vitro model system simulating a realistic patient specific model of the left ventricle and the thoracic aorta including the supra-aortic vessels. Systematic variation of the cannula position and remaining cardiac function were used to evaluate the impact of these boundary conditions on aortic hemodynamics.

Methods: An MR-compatible model system was developed consisting of an aorta connected to a paracorporeal LVAD (72 ml size) simulating the pulsatile flow of the native heart. The aorta was produced using rapid prototyping with an artificial resin to obtain a flexible character of the aorta. A LVAD was connected to the aorta model using three different cannula positions (A1: ascending aorta small anastomosis; A2: ascending aorta tall anastomosis, D: descending aorta, C: control; see Fig. 1). The boundary conditions given by the systolic and diastolic pressure and therefore the ejection fraction of the pulsatile LVAD as well as the frequency were controlled by a routine VAD control unit (MEDOS VAD-Driving Unit). Experimental setups were evaluated with a reduced cardiac output of the pulsatile LVAD and a LVAD (MEDOS Deltastream DP3) flow rate of 4 l/min and 5 l/min as well as no cardiac ejection and a LVAD flow of 5 l/min.

MR scans were performed on a 3T Trio Siemens system with a 12-channel thorax coil. A prospectively gated time-resolved 3D phase contrast sequence with 3-directional velocity encoding (venc=0.8-1.2 m/s) with an isotropic spatial resolution of 2.0 mm and a temporal resolution of 40.8 to 42.4 ms was applied to assess 3D hemodynamics in all LVAD models and all boundary conditions. A mixture of 60% distilled water and 40% glycerol representing the kinematic viscosity and density of blood was used. The fluid was doped with contrast agent (Gadovist, Bayer Healthcare) at 1.08 mmol/L, allowing a flip angle of 15°.

Four to six predefined analysis planes were positioned at different locations for all different model setups (Fig. 1 right panel) using EnSight (CEI; Apex, NC). For each plane, net flow, peak velocity and fraction of retrograde flow were determined using a home-built MatLab analysis tool.

Results: The results of the flow quantification are summarized in the table. For all different experiments the flow rates determined from plane 1 agree very well with the setting at the Deltastream LVAD (4 and 5 l/min). The sum of the flow through plane 1 and plane 2 for all experiments with the setups A1 and A2 agrees excellently with the flow through plane 3, as well as the through plane 4 and plane 5 with the value through plane 3 (C, A1, and A2). For setup D the subtraction of the flow between plane 6 and plane 5 agrees excellently with the value in plane 1. These results corroborate the robustness of the measured net flow values over the cardiac cycles in the different planes and experiments. With a reduced but residual cardiac output (as the typical scenario in patients with an LVAD), a higher flow rate in the proximal ascending aorta (plane 2) can be observed for A2 in comparison to A1, and a higher flow rate for A1 in comparison to D. The flow rates for the setups A1 and A2 are clearly higher with a lower flow of the LVAD (4 l/min) compared to the higher flow (5 l/min). The amount of retrograde flow in this plane is lower for setup A2 in comparison to A1 and D.

Discussion: For a residual cardiac output a taller anastomosis and a decreased flow rate of the LAVD yield in a higher flow rate and smaller retrograde flow in the ascending aorta compared to the smaller anastomosis or to the cannula position in the descending aorta. Pronounced flow turbulences in the aorta were observed for the cannula position in the descending aorta. Based on the observed results it may be assumed that – for a residual cardiac output – the optimal cannula position is given by the ascending aorta tall anastomosis. This may aid to better understand and prevent the progression of aortic valve regurgitation and thrombus formation.

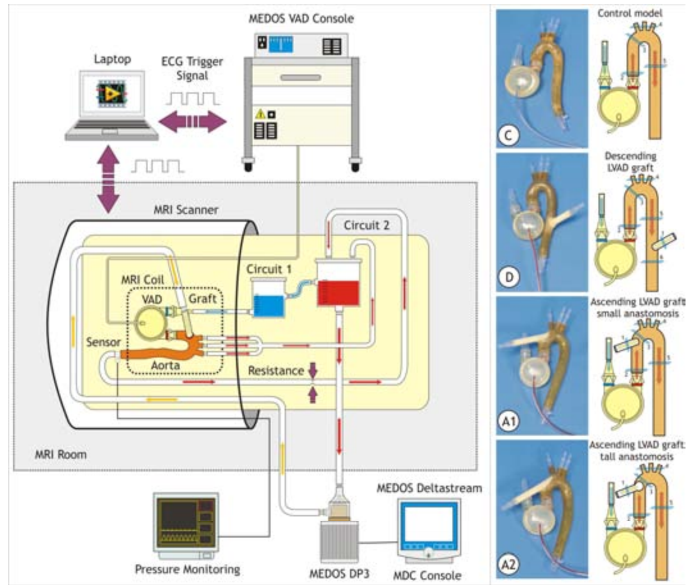

Fig. 1: Illustration of the model system to investigate different outflow cannula positions as illustrated in the right panel. The MR compatible VAD inside the scanner simulates the failing heart; the "true" VAD is positioned outside the scanner due to its non-MR compatibility (MEDOS DP3). In the right panel placed emitter planes for flow quantification are shown.

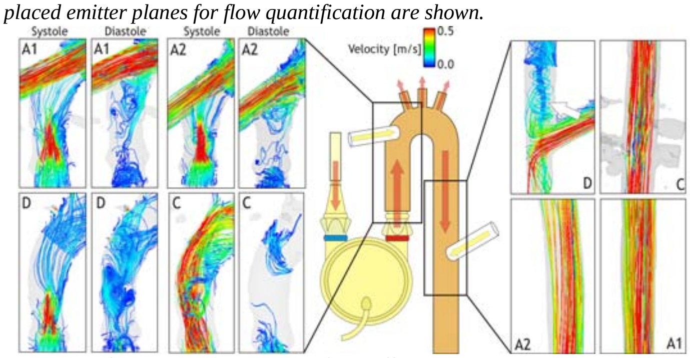

Fig. 2: 3D flow visualization in the four different models (C, A1, A2, D) during systole and diastole. Note the different systolic and diastolic filling patterns of the supra-aortic vessels for the different connections and the altered flow in the descending aorta regarding the LVAD outflow graft.

Model	C	A1	A2	D	A1	A2	D	A1	A2	D
Flow/Condition	Full ejection	LVAD = 4l/min, reduced CO			LVAD = 5l/min, reduced CO			LVAD = 5l/min, no CO		
Plane1 [l/min]	-	4,1	4,2	3,9	4,8	5,0	4,9	5,1	5,1	5,0
Retr. Flow [%]	-	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Plane2 [l/min]	4,1	0,9	1,0	0,6	0,6	0,9	0,6	0,0	0,0	0,0
Retr. Flow [%]	0,9	3,2	2,8	8,1	10	2,8	7,1	74	16	67
Plane3 [l/min]	4,0	5,0	5,2	0,7	5,7	5,8	0,8	5,0	5,1	0,1
Retr. Flow [%]	1,0	0,0	0,0	21	0,0	0,0	8,0	0,0	0,0	100
Plane4 [l/min]	0,8	1,1	1,3	1,0	1,3	1,5	1,1	1,3	1,3	0,9
Retr. Flow [%]	21	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Plane5 [l/min]	3,2	4,1	4,2	0,3	4,7	4,3	0,0	3,8	3,7	1,0
Retr. Flow [%]	5,1	0,0	0,0	33	0,0	0,0	50	0,0	0,0	100
Plane6 [l/min]	-	-	-	4,4	-	-	4,9	-	-	3,9
Retr. Flow [%]	-	-	-	0,0	-	-	0,0	-	-	0,0

References: [1] Fang JC. *N Eng J Med* 2009;361:2282-2285. [2] Cowger J et al. *Circ Heart Fail* 2010;3:668-674.