

Investigation of a ventricular assist device (VAD) in an in vitro model system using 4D-phase contrast MRI

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Target audience: Researchers who are interested in ventricular assist devices, hemodynamics, in vitro PC-MR Imaging.

Purpose: Ventricular assist devices (VADs) are an important tool for therapy in patients with heart failure to bridge the time gap for heart transplantations or as a permanent solution [1]. Various types of VADs are available with a variety of connection possibilities to the cardiovascular system providing a cardiac support with continuous or pulsatile flow. However, VADs can yield to alterations in the hemodynamic which can cause a higher thrombotic risk or the development of heart valve defects [2]. Due to the complexity only limited knowledge is available with respect to the impact of VADs on the hemodynamics. Therefore, it is of great interest to study the impact of different cannula connections and VAD operating conditions with in vitro model systems [3]. This work investigated the flow characteristics of a model system with a VAD blood supply via the right subclavian artery (RSA) as commonly used in cardiothoracic surgery in the recent past (CircuLite® system, NJ, USA). 4Dphase contrast (PC)-MRI was used for qualitative and quantitative evaluation of flow characteristics.

Methods: Measurements were performed on a 3T Trio Siemens system. The MR compatible in vitro model system consisted of two flow circuits (Fig. 1). The first circuit (depicted in blue) simulated the normal blood circulation from the LV into the aorta and back through a reservoir to the LV. An MR compatible pneumatically driven pulsatile VAD (PVAD) with 60 ml pump volume (MEDOS, Stolberg, Germany) was mimicking the native (failing) heart (60 bpm). The aorta consisted of synthetic resin (Biresin®U1404, Sika GmbH, Germany) to simulate the elastic property of the human aorta. Its shape was modeled based on a 3D data set of a human [3]. The second closed circuit (red) included the VAD (non-MR compatible, outside the scanner room) consisting of a diagonal pump (DeltaStream MEDOS, Stolberg, Germany) that provides a continuous flow (CVAD) and that was supplied by a reservoir. The aorta was supplied from the connected CAVD (Fig. 2, Pos. 6) via a retrograde flow through the subclavian artery (Pos. 7) and the brachiocephalic artery (Pos. 5). The PVAD was operated in three modes: Complete filling and emptying of the PVAD was applied as a baseline (Reference). To simulate heart failure, the PVAD was operated with a reduced cardiac output of about 2/3 (Red1) and 1/3 (Red2) of the baseline cardiac output (CO). Additionally, the CVAD was operated with 2, 3, and 4 l/min. To simulate realistic conditions, about 1/3 of the flow volume from the ascending aorta left the supra-aortic branches and about 2/3 was flowing through the descending aorta. To simulate the viscosity of blood a water-glycerol mixture (60-40%) was used.

4D PC-MR-flow measurements of the aorta model system were performed with 3-directional velocity encoding of 150 cm/s, a spatial resolution of 1.4x1.4x1.4 mm³, a temporal resolution of 42.4 ms resulting in 23 time frames within one cardiac cycle. Measurements with flow and without flow were subtracted to correct for Eddy current related phase offsets. In-house built Matlab software tools were applied to quantify the total flow [l/min] and the amount of retrograde flow [%] in 10 planes as shown in Fig. 2. The blood flow was visualized in a qualitative manner using particle traces (EnSight, CEI Inc., Apex, NC, USA) with respect to flow characteristics such as vortices or recirculation zones.

Results: Values of the total flow and retrograde flow at positions 1, 4, 5, 6, 7, 8 are listed in Tab. 1 for the baseline and the two cases with a reduced CO in combination with an operating CVAD at 2 and 4 l/min. The total flow was about zero with no CVAD support (Pos. 6) as expected, but systematically higher than the provided 2 and 4 l/min of the CVAD. Beside the inverted flow in Pos. 5, the CVAD caused a decrease of the total flow in the ascending (Pos. 1) and an increase of the total flow in the descending (Pos. 4) aorta. Furthermore, the CVAD caused an increase of the total flow in the RSA (Pos. 7), whereas it had only a minor impact on the right (Pos. 8) and left (Pos. 9) carotid artery and the left subclavian artery (Pos. 10). No or only minor retrograde flow was observed at Pos. 3, 4, 6, 7, 8, 9 and 10 for both CVAD support rates and both CO conditions. The first and second graph on the left in Fig. 2 show streamline visualization of the reference (no CVAD) and strongly reduced CO conditions with the higher (retrograde) velocities in the brachiocephalic artery caused by CVAD. The two graphs on the right in Fig. 2 show streamlines originated from the CVAD (Pos. 6, yellow), clearly demonstrating blood flow partly down the ascending aorta against the actual flow direction, and from the PVAD (Pos. 1, red).

Discussion: The investigation of the flow characteristics inside the aorta and its upper branching vessels revealed that the RSA and the right carotid artery were solely supported by the CVAD for all operating conditions (2,3,4 l/min) whereas the descending aorta was supported by both the PVAD, i.e. the native failing heart, and the CVAD. Thus, the operating condition of CVAD should be carefully adjusted to the residual function of the failing heart to minimize the amount of blood flow from the brachiocephalic artery down the ascending aorta and therefore minimizing additional loading from the CVAD on the failing heart. The flow rates in the brain-feeding arteries are only marginally affected by CVAD conditions. The retrograde flow in the ascending aorta was about twice as much as in the baseline if a high continuous flow of 4 l/min was applied. This might affect e.g. the functionality of the aortic valve and the residual performance of the native heart. On the other hand, the blood circulation of the coronary arteries may be improved. In the future, additional measurements are required to determine systematical errors of the model system. Furthermore, flow data of patients acquired with Doppler ultrasound could be used for a comparison of in vitro and in vivo results.

Acknowledgements: German Research Foundation (DFG) Grant JU 2687/9-1

References: [1] Fang 2009 N Engl J Med. 3;361:2282-5. [2] Litwak et al. 2004 ASAIO J. 50:432-7. [3] Benk et al. 2013. Eur. J Cardio-Thoracic Surgery 1-8.

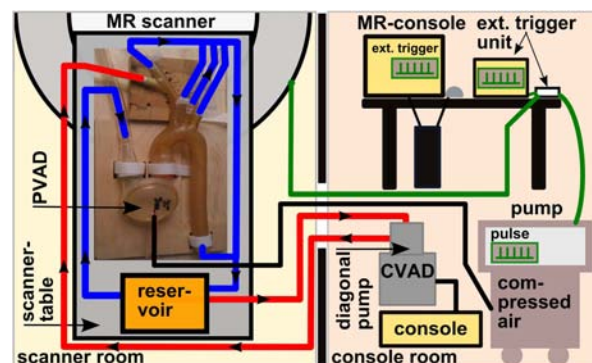


Fig.1: Measurement setup. (green cables: Connection to allow triggering for MR measurements)

Total flow [l/min]:					
Pos.	Ref.	Red1(2l/min)	Red1(4l/min)	Red2(2l/min)	Red2(4l/min)
1	3.90	2.98	2.42	2.31	1.66
4	2.61	3.10	4.20	2.67	3.91
5	0.66	-1.29	-3.23	-1.25	-3.52
6	-0.05	2.43	4.75	2.28	5.00
7	0.39	0.60	0.76	0.43	0.81
8	0.41	0.51	0.55	0.42	0.37
Retrograde flow [%]:					
1	1.5	1.7	3.1	1.3	4.0
4	3.0	0.0	0.0	0.0	0.0
5	29.0	92.2	100.0	95.6	100.0
6	-	0.0	0.0	0.0	0.0
7	20.0	3.9	0.0	3.2	0.0
8	17.0	6.5	3.3	5.8	5.1

Tab.1: Total and retrograde flow of baseline (Ref.) and PVAD with reduced cardiac output (Red1,Red2) combined with two different support rates of the CVAD (2 and 4 l/min).

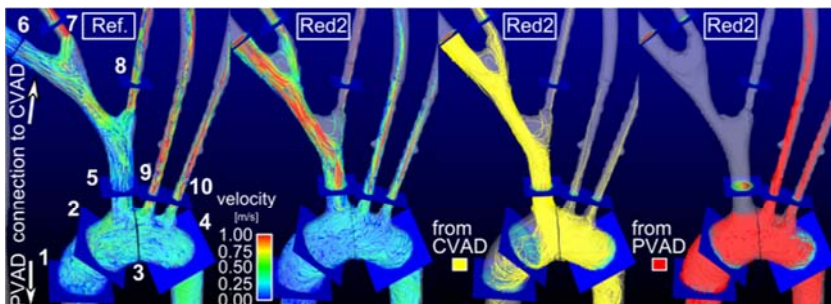


Fig.2: Total and retrograde flow determined at positions 1 to 10. Reference and Red2 with CVAD providing 4 l/min cont. flow are depicted.