Analysis of 3D Flow Dynamics in a Ventricular Assist Device by Flow Sensitive 4D MRI

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Introduction: Mechanical circulatory support using ventricular assist devices (VAD) has evolved as a realistic therapeutic option for patients in end-stage heart failure [1, 2]. However, some severe potentially flow related lethal and devastating complications remain after VAD implantation, including thrombus formation and embolization, infections and device failures [3]. To investigate blood flow in a VAD, an ideal approach would require direct assessment of flow characteristics *in-vivo*. However, implanted VADs are not MR compatible and *in-vivo* flow studies can thus not be performed directly. In order to enhance the understanding of flow characteristics within VADs, it is therefore of great interest to provide a realistic *in-vitro* VAD model system [4]. The overall aim of this study was to test the feasibility of an MR compatible VAD system and to perform flow-sensitive 4D MRI measurements for the assessment of 3D flow dynamics inside an operating clinical routine VAD [5]. Specifically, the in-flow conditions were adjusted to match the blood flow characteristics typically used *in-vivo* by using an identical control and pump unit.

Methods: A commercial VAD (MEDOS, Stolberg, Germany) was integrated into a MR-compatible flow circuit including PVC tubes, a reservoir to flow resistance, and an air pressure pump. The pump and control unit consisted of a clinical routine device (MEDOS VAD-Driving Unit, Stolberg, Germany) used for *in-vivo* VAD operation which was modified by using long tubes (approximately 8 meters) to connect the pump unit outside the MR room to the VAD circuit inside the MR scanner. Periodic pressure waveforms were transferred to the VAD circuit to generate pulsatile flow (systolic pressure = 180 mmHg, diastolic pressure = -20 mmHg, systolic fraction = 35 % of flow cycle) within the VAD model system (figure 1).
All MR experiments were performed using a 3T MRI system (TRIO, Siemens, Germany) using time-resolved 3D phase contrast MRI (flow sensitive 4D-MRI) with interleaved 3-directional velocity encoding (spatial resolution = $2.0 \times 1.9 \times 2.0$ mm³, flip angle =15°, TE/TR=3.7/6.1ms, velocity sensitivity venc=150cm/s). Measurements were prospectively gated to the RR-interval simulated by the pump system and 14 time frames with a temporal resolution of 48.8ms were collected within the flow cycle.
Following noise masking and eddy current correction, the measured velocity data were loaded into a 3D visualization software package (EnSight, CEI, USA). Vector graphs were generated on predefined 2D cutplanes and illustrated the direction and magnitude of the measured flow velocities within the flow cycle. 3D stream-lines represent traces locally parallel to the three-directional flow velocity field [6].

Results: Figure 2 illustrates results of time-resolved vector graph visualization in user selected planes transecting the VAD. During filling of the VAD chamber (figure 2A) high and accelerated flow at the inlet can clearly be appreciated. Note that vector field visualization detected an unwanted small retrograde flow channel (open yellow arrows) near the out-flow region directed backwards into the VAD chamber indicating valve insufficiency at the outlet. Moreover, the path of the VAD filling channel and the existence of circular flow inside the expanded VAD chamber are clearly visible. During outflow (figure 2B) accelerated flow velocities distal to the outlet valve (figure B1) acre clearly visible. Most noticeably, magnified vector fields near the inlet valve (figure B2) revealed the existence of a marked flow vortex (solid yellow arrow) pointing towards recirculation zones at risk for thrombus formation.
3D stream-line visualization demonstrated complex flow patterns ranging from flow channels along the VAD border during filling followed by circular flow patterns and vortex formation in the VAD lumen. During filling (figure 3) A flow channel through the entire VAD connecting accelerated inflow near the inlet valve (yellow arrows) and the out-flow tract can clearly be appreciated. Flow channels along the borders of the VAD volume persisted throughout the entire flow cycle.

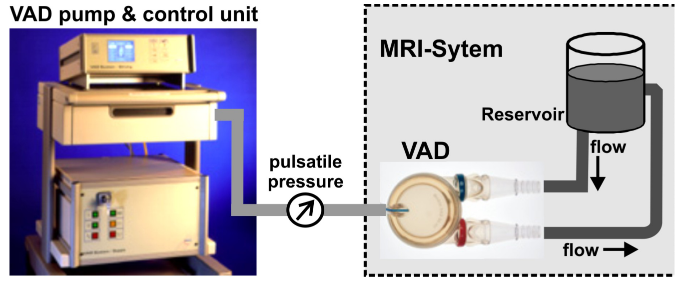

Fig. 1: Schematic setup for VAD flow analysis. A clinically used VAD was integrated into to a closed flow circuit and connected to a control and pump unit. Periodic pressure variation identical to *in-vivo* VAD operation was used to generate pulsatile flow within the VAD model system.

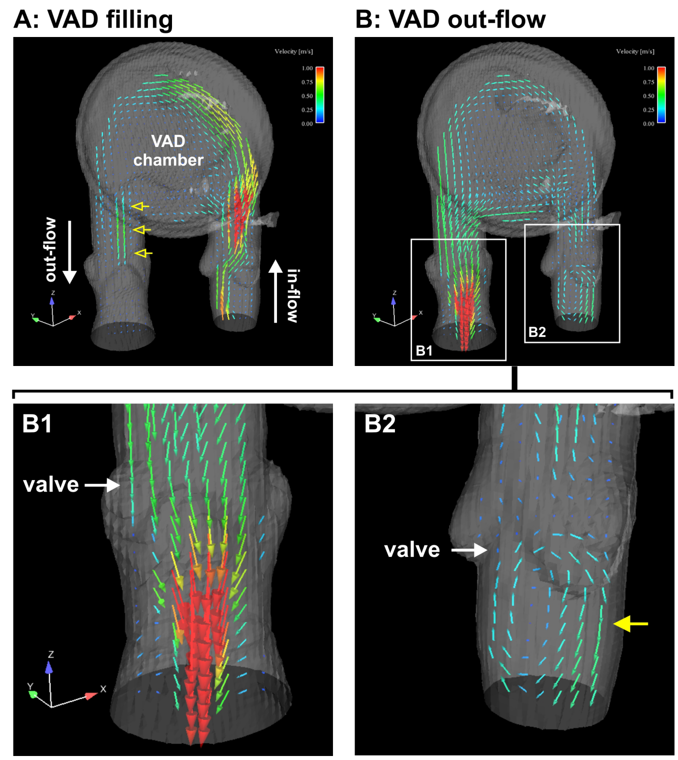

Fig. 2: Detailed 3D flow characteristics during the filling (A) and out-flow (B) phase of the VAD. Visualization of the measured flow velocities was performed as three-directional vector graphs in planes transecting the VAD chamber as well as in- and out-flow channels.

Discussion: The integration of a VAD model system into an optimized pulsatile flow circuit in combination with the application of flow sensitive 4D MRI permitted detailed analysis of flow characteristics in a realistic environment resembling *in-vivo* conditions. Flow sensitive 4D MRI may thus have the potential to enhance the understanding of flow characteristics inside VAD systems with different size, geometry and in-flow conditions, i.e. non-pulsatile versus pulsatile flow. Moreover the detailed visualization flow patterns and/or local changes in flow velocities may help to identify vertical or helical flow regions inside the VAD geometry which are likely to develop thrombi or other functional deficits which may impair VAD performance. As a long-term objective, such model systems could also be used to optimize the design of VADs and to test different in-flow conditions and their effects on the blood flow characteristics and VAD performance. Limitations of this study include that the inflow boundary characteristics may have been altered compared to in-vivo conditions due to the long tubes that were necessary to the deliver the periodic pressure changes to the VAD system. Further studies are thus planned using modified VAD systems without metal components and a more precise generation of inflow conditions.

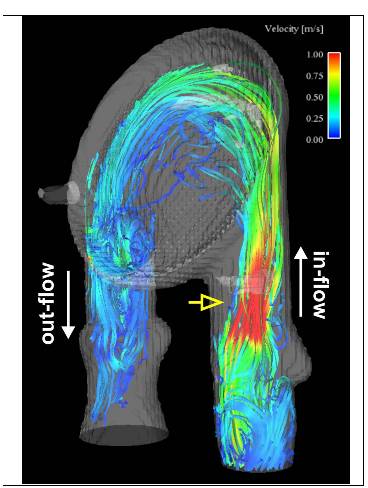

Fig. 3: Stream-lines illustrating 3D flow characteristics inside the VAD during filling and initial out flow for the same time frame as figure 2A. Accelerated flow at the inlet (yellow arrow) is evident.

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