

Phase Contrast MRI Velocimetry of a Stereolithographic Total Cavopulmonary Connection at 1.5 T and 3 T

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Background: As surgical planning approaches clinical feasibility, patient-specific flow quantification is of increasing interest. MRI is aptly suited to this purpose, where accurate anatomic information can be attained during an *in vivo* scan, and more recently, phase contrast MRI can be employed to extract hemodynamic details. Thus the applications of MRI for flow quantification continue to expand.

The Fontan operation, one such relevant instance, is used to palliate cyanosis in single ventricle patients present in two per every 1000 live births. Acting as a bypass of the right heart, the total cavopulmonary connection (TCPC) is a Fontan anastomosis of the superior and inferior venae cavae (SVC, IVC) to the left and right pulmonary arteries (LPA, RPA), thereby separating the systemic and pulmonary circulations. Detailed TCPC fluid dynamics are of interest in order to minimize power dissipation. Such efficiency is critical to alleviate the weakened circulatory system powered solely by a single systemic pump.

As MRI evolves toward higher field strengths, questions loom as to its advantages in phase velocity mapping. Recent literature reports on *in vitro* flow experiments in 3 T scanners have been of idealized models in theoretical flow regimes [1]. As such, the feasibility of using 3 T phase contrast MRI for hemodynamic flow extraction in complex anatomies has yet to be thoroughly examined. Here, we examine the differences in flow fields of a patient-specific TCPC at 1.5 T and 3 T.

Methods: A hypoplastic left heart syndrome patient with a lateral tunnel TCPC is enrolled for MRI study. The study protocol includes a balanced fast-field echo (FFE) sequence (50 static contiguous transverse slices, 4 mm slice thickness, 1 mm in-plane resolution) for delineation of TCPC vasculature and phase contrast MRI sequences (single plane perpendicular to investigated vessel at 20 cardiac phases, 5 mm slice thickness, 0.7 mm in-plane resolution) for flow quantification in the SVC, IVC, LPA, and RPA.

The images from the balanced FFE sequence are interpolated in the through-plane direction, segmented, reconstructed to a 3-D anatomy, inverted in computer-aided design, and prototyped as an anatomically accurate stereolithography model for *in vitro* flow experiments according to previously established protocol [2] and as seen in Figure 1.

The anatomic replica is then placed in a steady flow loop of water-glycerin, using to mimic blood kinematic viscosity at 3.5 cSt, as in the schematic of Figure 2. Transverse phase contrast MRI scans are acquired in Philips Intera 1.5 T and 3 T scanners with 50 contiguous slices of 2 mm thickness and 0.4 mm in-plane resolution. All three velocity components are acquired, interpolated in the through-plane direction in-house, and processed off-line in Tecplot. An in-house 3-D rigid-body image registration code superimposes the 1.5 T and 3 T scans. Velocity vectors from the 3 T scan are interpolated onto the 1.5 T velocity field for direct quantitative comparison.

Flow rates are obtained from the phase contrast MRI sequence to obtain a patient-specific resting cardiac output of 4 L/min. An SVC/IVC flow rate ratio of 40/60 is used with varying LPA/RPA flow rate ratios of 30/70, 50/50, and 70/30. Exercise cardiac outputs of 6 L/min and 8 L/min are also examined.

Results and Discussion: Velocity fields at 1.5 T and 3 T are shown in Figure 3. In addition, 3-D image registration allows a direct comparison between the two flow fields. The qualitative similarity of the 1.5 T and 3 T flow fields is evident, signifying the potential for 3 T phase contrast MRI velocimetry in complex anatomies.

The cross-sectioned flow fields in Figure 3 suggest skewing toward the posterior side of the IVC. Such asymmetry is likely due to the anterior pouch created by the lateral tunnel construction during surgery. Such an area of low flow may give rise to poor washout and increased hemodynamic power losses. Similar flows can also be seen in Figure 4, where the SVC and IVC stream impinge and recirculate at the location of the black box in Figure 1. Despite qualitative parallels, the difference plot in Figure 3 and recirculation zones in Figure 4 do reveal higher velocities in the 3 T scan. Such discrepancies could be attributed to noise clip factors that were enabled in the 1.5 T scan, but disabled in the 3 T scan to prevent possible data filtering. Nevertheless, the flow disparities warrant further investigation.

Conclusions: Given phase contrast MRI at high SNR, flow quantification of comparable quality to a 1.5 T scan can be expected from 3 T imaging. These data suggest that complex anatomic flow structures can be represented through three-component *in vitro* phase contrast MRI, but deserve additional scrutiny for quantitative validation.

References

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2. de Zelicourt, D., et al., *Single-step stereolithography of complex anatomical models for optical flow measurements.* J Biomech Eng, 2005. **127**(1): p. 204-7.

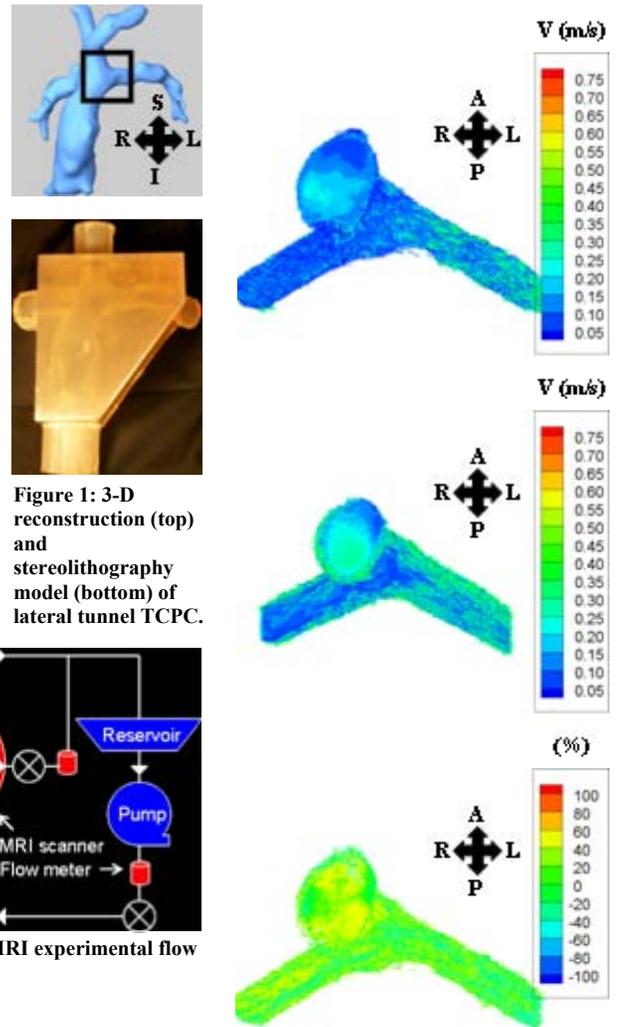


Figure 1: 3-D reconstruction (top) and stereolithography model (bottom) of lateral tunnel TCPC.

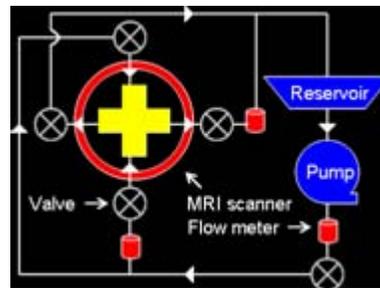


Figure 2: In vitro MRI experimental flow loop.

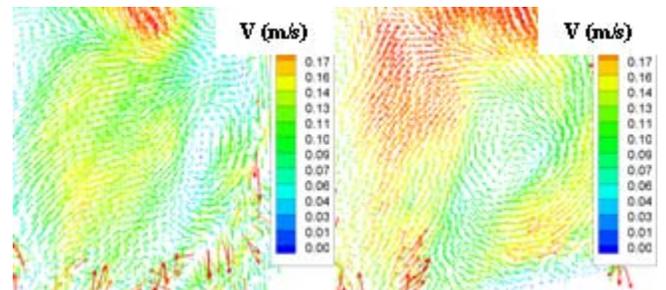


Figure 4: Colliding SVC and IVC streams at 1.5 T (left) and 3 T (right) at the location of the black box in Figure 1 (bottom).