THE INFLUENCE OF GEOMETRIC AND IN-FLOW BOUNDARY CONDITIONS ON PATIENT-SPECIFIC COMPUTATIONAL FLUID DYNAMICS IN A FONTAN PATIENT POPULATION

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Target audience: Radiologists and researchers interested in power loss calculations inside Fontan circuit.

Purpose: One of the most severe congenital heart diseases is found in infants born with hypoplastic left or right heart syndrome with only one fully functioning ventricle. Patients undergo multiple successive surgical interventions to reconstruct their cardiovascular system into the single ventricle physiology. The final surgical procedure creates the Fontan circulation which results in systemic venous return being supplied directly to the lungs through the pulmonary arteries without passing through the right ventricle as in normal cardiovascular physiology [1]. There is growing evidence that the hemodynamics of the Fontan connection may play an important role related to patient outcome [2]. Patient specific computational fluid dynamics (CFD) has been used in a number of studies to derive Fontan 3D flow patterns and has helped to provide a better understanding of the impact of the individual Fontan geometry on Fontan hemodynamics [3]. However, CFD relies on the accurate definition of geometric and in-flow boundary conditions derived from MR imaging. The information on the geometry of the Fontan circuit is mostly obtained from anatomical (magnitude-based) MRI images, while blood flow and the power loss are derived from phase-contrast MRI (PC-MRI) data and subsequent CFD simulations. Although the methodological approach to obtain these quantities is similar, the results in the literature show large discrepancies [4]. While the subject-specific conditions of these patients often drive these differences, segmentation errors may also be a contributing source of error. To date, the impact of observer variability in the segmentation of the 3D Fontan geometry on the CFD results has not been systematically investigated. In this study, our aim was to investigate the influence of segmentation on the estimated lumen size, the MRI derived in-flow boundary conditions, and the CFD derived 3D velocity field and power losses inside the Fontan circuit.

	Observer	IVC	SVC	LPA	RPA
Diameter [cm]	1	1.7±0.6	1.3±0.2	1.3±0.3	1.4±0.6
	2	2.0±0.7	1.6±0.3	1.5±0.4	1.6±0.6
Mean Flow [mL/sec]	1	29.2±20.1	14.0±7.0	16.2±9.7	25.6±24.6
	2	36.1±24.6	16.9±7.4	19.8±13.2	29.3±26.9

Table-1: The lumen diameter [cm] and the mean flow [mL/sec] of IVC, SVC, LPA and RPA derived from MRI by two blinded observers.

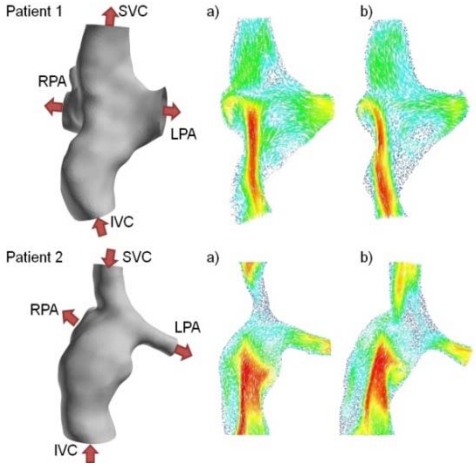

Figure-1: The segmentations (Left) and the CFD based velocity vectors (Right) obtained using segmentation of a) observer-1 and b) of observer-2 for 2 representative cases. Velocity vectors are shown for one cross-section in the same color scale.

Methods: 4D flow MRI was performed in 6 Fontan patients (age: 9-21, 5 male) with whole heart coverage (spatial resolution: 1.9-2.5 x 1.9-2.5 x 2.2-3.3 mm^3, temporal resolution: 38.4-41.6ms, venc: 100-150 cm/s, TR: 2.36-2.72ms, TE: 38.4-41.6ms, flip angle=15°) using a 1.5 T system (Avanto or Aera, Siemens, Germany). The 4D flow data was used to derive both geometric and in-flow boundary conditions for CFD. 3D segmentation of the Fontan connection was performed manually by two blinded observers. The images used by the observers to segment the volumes of interest were fundamentally different. Observer-1 performed 3D segmentation based on 3D phase-contrast angiogram (PC MRA) data (time-averaged velocity magnitude weighted by magnitude data) [5]. Observer-2 segmented time-averaged phase contrast magnitude images. This approach is an example of a 'worst case' situation when attempting to minimize observer variability in segmentation. The lumen diameter and the time averaged blood flow of the inferior vena cava (IVC), superior vena cava (SVC), left and the right pulmonary arteries (LPA and RPA) were calculated for both segmentations. 3D Fontan segmentations were converted to volumetric meshes with an element size of 0.06mm. Time resolved CFD simulations were performed by using MRI based IVC, SVC and RPA flows as the boundary conditions. LPA was left as stress free. The CFD based mean and the peak (top 5%) velocities in 10 time points were compared for two segmentations with Bland-Altman analysis. The CFD based pressure and velocities were then averaged over time to calculate cycle averaged power losses using the control volume approach and the mechanical energy balance equation as in [4]. Statistical significance was tested with two-sided paired t-test.

Results: The segmentation of observer-1 resulted in 15±3% smaller lumen diameters than those performed by observer-2 ($p<0.01$, Table-1). Similarly, the MRI derived in-flow boundary conditions inside the arteries were found to be 17±3% lower by observer-1 ($p<0.01$, Table-1). Despite differences in the artery diameters and in-flow boundary conditions, CFD results showed similar flow patterns as in the representative two cases presented in Figure-1. The differences in CFD based mean and peak velocities between two segmentations are shown with Bland-Altman plot in Figure-2. The cycle averaged power loss was found to be 8.5±11% lower by observer-1 relative to those obtained by observer-2 (1.1±1.1mW vs. 1.3±1.2mW respectively, $p=0.10$).

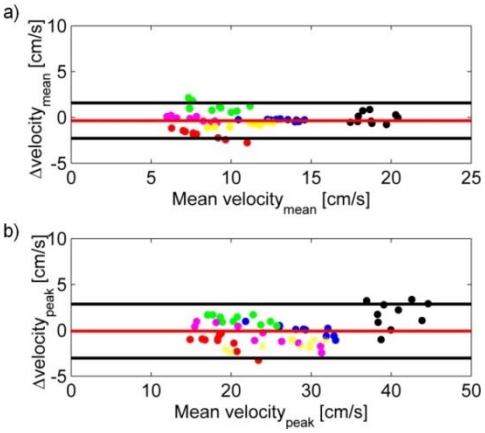

Figure-2: The Bland-Altman plots of CFD based a) mean velocities (mean: -0.4 cm/s and 95% limits of agreement: -2.3 to 1.6 cm/s) and b) peak (top5%) velocities (mean: -0.1 cm/s and 95% limits of agreement: -3.0 to 2.9 cm/s) at 10 time points in the cardiac cycle obtained with two different segmentations. Different colors represent different patients.

Discussion: The lumen cross-sections may appear larger or smaller than its actual size depending on the method of segmentation and type of MRI image used. This, combined with observer variability, was the primary cause for variability when estimating the lumen size. Additionally, the difference in the estimated lumen size translates to the measured flow rates, velocities and the calculated power losses. The overestimation of lumen size increases the estimated flow rates and also power losses (but to a lesser extent). Although the difference in magnitude of the power loss was small (0.2 mW), it still resulted in an 8% difference. This illustrates the importance of minimizing segmentation variability when computing CFD derived parameters, such as power loss. Nevertheless, observer differences in the CFD findings were small and, most importantly, relative inter-patient differences were maintained, indicating the robustness of CFD with respect to variability in boundary conditions. It is therefore important to use one approach and image type in segmentation in studies comparing different patient groups.

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