Flow field comparison in reverse engineered total cavopulmonary connection anatomic models: High Resolution PC MRI vs CFD

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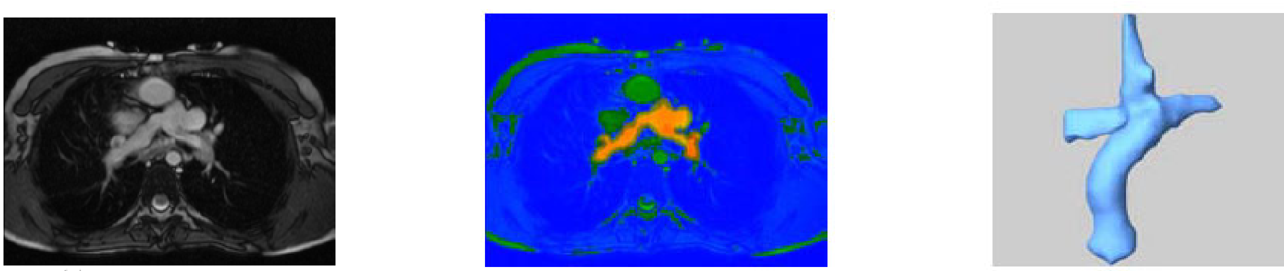
Introduction

Congenital heart disease can take a variety of forms. 2 out of 1000 live births result in morphological defects characterized by a single ventricle physiology, where systemic, oxygenated blood mixes with pulmonary, deoxygenated blood via a single pumping chamber. Disorders that fall within this classification include hypoplastic left heart syndrome, tricuspid atresia, double outlet ventricle, septal defects, heterotaxy syndromes, and transposition of the great arteries. The current preferred Fontan procedure for surgical palliation of single ventricle patients is the total cavopulmonary connection (TCPC). In the TCPC, the inlet flows from the Superior Vena Cava (SVC) and the Inferior Vena Cava (IVC) are directed to the Left Pulmonary Artery (LPA) and the Right Pulmonary Artery (RPA). Fluid dynamic efficiency is key in the TCPC because the right heart is bypassed. High-resolution 3D PC MRI holds promise in providing detailed flow structures and efficiency in the TCPC, though it takes a prohibitively long time to acquire them *in vivo* from patients who have undergone the palliation. However, creating an anatomic model associated with the TCPC using patient MRI can circumvent this problem. In this study, a stereolithographic anatomic model was created using patient MRI and flow experiments were conducted using this model at physiologic flow rates to acquire high resolution PC MR images. The flows reconstructed using these images were qualitatively and quantitatively compared to numerically computed CFD results.

Methods

An MRI database of 86 patients aged between 2-25 has been developed in order to characterize the TCPC geometry. For this study, a patient with an extra cardiac TCPC was analyzed. A stack of 22 contiguous axial MRI slices each with a slice thickness of 5 mm spanning the entire TCPC was obtained (Figure 1a). These images were interpolated using an optical flow based directional interpolation technique in order to achieve an isotropic voxel size. The TCPC was segmented using in house code, and the segmented slices were imported into commercial software in order to create a smooth 3D reconstruction of the geometry (Figure 1c). A stereolithography (STL) model was created using the 3D reconstruction. A physical model was then manufactured in the rapid prototyping laboratory using this STL model (Figure 2a). An MRI flow loop experiment was setup using this model in a Philips Intera 1.5T MRI scanner. Flow experiments were done using cardiac outputs of 2, 3, and 4 liters per minute, with LPA flows varying from 30% to 70%. High resolution axial PC MRI were acquired with phase encoding in all three directions, an FOV of 102.4 mm, slice thickness of 2 mm, and a matrix size of 128 x 256 pixels. The images were interpolated to an isotropic voxel resolution (0.4mm X 0.4mm X 0.4 mm) using the technique mentioned above. A CFD analysis was performed for each of the physiologic flow rates observed. The flow fields for each of the cases were reconstructed, and the results were compared to the numerically computed flows using CFD.

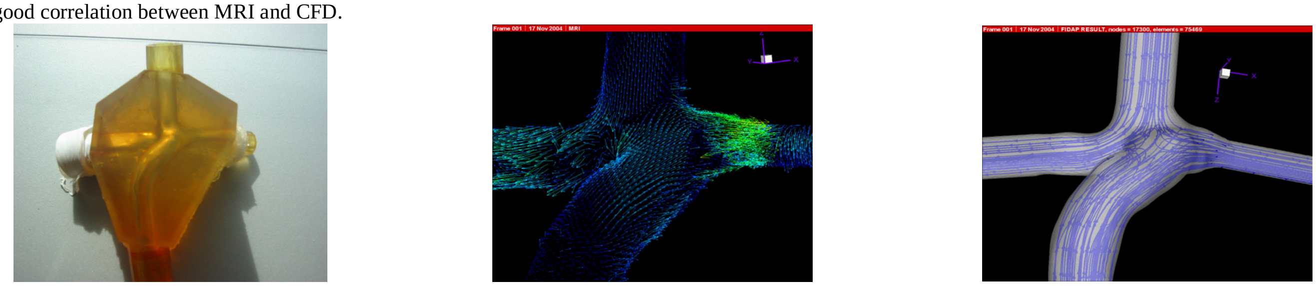


a.) *b.)* *c.)*

Figure 1: The process of model generation from segmentation to 3D reconstruction

Results

For each of the flow rates mentioned above, the flow structures and velocity maps obtained using PC MRI were compared to those numerically obtained using CFD. A snapshot of this flow field reconstructed from 3D PC MRI and the corresponding CFD flow field for a flow rate of 2 L/Min, and an LPA – RPA flow split of 50-50 is shown in Figure 2. A qualitative comparison of the flow structures and a quantitative comparison of the velocity maps yielded a good correlation between MRI and CFD.



a.) *b.)* *c.)*

Figure 2: a) A physical anatomical model used for running the experiment, b.) MRI flow field reconstruction, c.) CFD results

Discussion

Understanding the flow dynamics in the TCPC is an important precursor for planning the surgeries associated with single ventricle defects. PC MRI makes it possible to look at 3D flows *in vivo*, which makes it important that its accuracy and efficiency in imaging flows within complex vascular geometries be evaluated. However, high-resolution 3D PC MRI acquisition is a time consuming process, and it presents a practical problem to acquire them from patients with the TCPC. For this reason, anatomic models were built using rapid prototyping in order to acquire images with the necessary resolution for 3D flow field reconstruction. A good match between the flow fields acquired using MRI with CFD shows that 3D PC MRI is quite effective in imaging flows in TCPC geometries and hence could prove valuable for surgical planning.