Ventilator Gated 4D Flow MRI in Pediatric Patients with CHD: Initial Feasibility and Internal Validation

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TARGET AUDIENCE: Radiologists and researchers interested in using 4D-flow MRI to assess pediatric congenital heart abnormalities.

PURPOSE: Contrast enhanced MR angiography (CE-MRA) and 2D phase contrast imaging are well established methods of non-invasively assessing structural and functional abnormalities in pediatric patients with congenital heart disease (CHD).[1,2] More recently, 4D-flow MRI has emerged as a promising method for visualizing and quantifying complex flow patterns in these same patients.[3] Since young patients (<~7 years old) and those in critical condition have difficutly complying with breath-held instructions many institutions prefer using general anesthesia with mechanical ventilation support. The purpose of this study was an initial evaluation of a 4D-flow workflow consisting of: 1) a ventilator-gated 4D-flow acquisition that leverages the regularity of respiratory motion provided in these cases; and 2) 4D flow segementation using a recently developed[4] co-registered, high resolution, ventilator gated, CE-MRA technique made possible through the use of an intravascular contrast agent (Ferumoxytol).

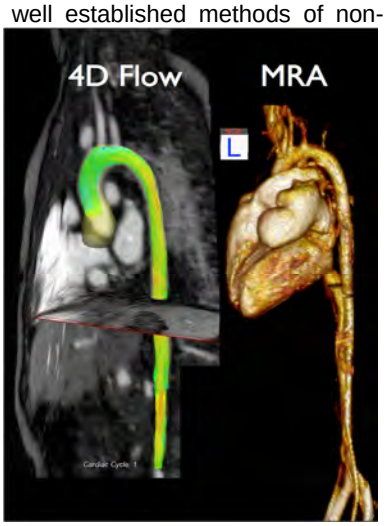

Figure 1: Example of MRA data used for initial segmentation and corresponding 4D flow results.

METHODS: 4D flow MRI[3] was modified for ventilator-gated acquisition (TE/TR=2.52-3.02 /14.5-35.5 ms, temporal resolution=58-143 ms, voxel size 1.56-2.4mm^3, venc=100-250cm/s, flip angle=20-25°, bandwidth=635-829Hz/pixel, 5-9 cardiac phases) and acquired in a cohort of pediatric patients with CHD (N=9; aged 4 days to 19 years). All studies were performed on a 3.0T MRI scanner (Siemens Trio). A gating window positioned at end-expiration with a 30% threshold defined the acceptance window for data acquisition. A co-registered high resolution CE-MRA using MUSIC[4] with Ferumoxytol was also acquired. 4D flow and MUSIC data were imported into an investigational 4D flow evaluation prototype (version 2.4[5], Siemens AG, Erlangen, Germany) and semi-automated centerline extraction and lumen segmentation were performed in all vessels of interest using a combination of 4D flow data and one cardiac phase of the MUSIC data.[6-7] Net forward flow, average flow, and peak velocities were measured in all patients (except where impossible due to susceptibility artifacts) in planes placed orthogonally to the segmented vessel within the 4D flow data at the following locations: in the ascending aorta (aAo), immediately after the subclavian artery, and superior and inferior to the renal arteries; at the main pulmonary artery (MPA) and left and right branches (LPA and RPA); and in the inferior and superior venae cavae (IVC and SVC) proximal to the right atrium. In four patients, 2D PC-MRI data were available for quantitative comparison to 4D flow and retrospectively analyzed in the aAo, MPA, or RPA.

Analysis Planes	Net Flow ± SD [mL]	Bias ± 1.96*SD [mL]
Systemic Flow vs MPA	25.54±16.40	-6.63±14.16
Systemic vs (RPA + LPA)	22.63±13.30	3.74±25.22
Systemic vs. (SVC+IVC)	23.55±15.73	-1.73±21.99
MPA vs. (RPA +LPA)	26.36±17.06	5.12±23.31
MPA vs. (SVC+IVC)	27.28±18.85	1.65±22.68
(RPA+LPA) vs. (SVC+ IVC)	24.20±16.21	1.19±13.75

Table 1: Bland altman comparison of net forward flow through systemic circulation (Ao), pulmonary circulation (MPA and LPA + RPA) and venous return (SVC +IVC). Average net flow provided as a benchmark.

RESULTS: *Internal Validation* - Table 1 summarizes net flow agreement between planes. When compared to net flow in the ascending aorta, net flow in the aorta decreased distally by an average of 32.7%, 46.8%, and 72.0% in planes immediately distal to the subclavian artery and proximal and distal to the renal arteries respectively. Average peak velocities in these planes were 94.2, 98.8, 112.8, and 94.1 cm/s respectively. All patients showed a trend of decreasing net flow volume along the aorta and all but one showed a trend of increasing peak velocities from ascending aorta to renal arteries. *Comparison with 2D PCMRI* - In five total planes in three patients, net forward flow in the 4D flow data differed by 3.31%±19.55% compared to 2D PCMRI data. Data from one patient was discarded due to severe flow aliasing artifacts. *Impressions during processing* - Co-registered high resolution MRA data for segmentation during 4D flow processing greatly facilitated the accuracy of the initial semi-automatic masking step – especially in smaller vessels and complex anatomies (Figure 1). This reduced the need for further manual correction and simplified processing complexity.

DISCUSSION: These initial results demonstrate that a workflow consisting of ventilator gated 4D flow acquisition coupled with segmentation using the MUSIC MRA sequence made possible by an intravascular contrast agent is feasible and provides a straightforward workflow. Systemic, main pulmonary, sum of left and right pulmonary, and venous return through plane flow volumes had low mean differences and moderate limits of agreement. As expected, flow volume decreased along the aorta when moving past branching vessels. Peak velocity estimates increased along the thoracic aorta until after the renal arteries and their values were within the range of those previously reported[8]. Further development and implementation of image acceleration techniques such as compressed sensing or kt-GRAPPA parallel imaging to reduce scan time and improve spatial and temporal resolution is certainly warranted.

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