Analysis of Right Atrial and Ventricular Flow Patterns with Whole Heart 4D Flow MRI – Comparison of Tetralogy of Fallot with Normal Volunteers

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Introduction: Tetralogy of Fallot (TOF) – consisting of ventricular septal defect (VSD), pulmonary stenosis (PS), over-riding aortic root, and right ventricular hypertrophy (RVH) – is the most common cyanotic heart defect and accounts for nearly 10% of all congenital heart defects. Following repair, patients with TOF frequently have pulmonary regurgitation (PR) and residual or recurrent pulmonary artery (PA) stenosis which contribute to the progressive development of right ventricular (RV) dilation and failure. Cardiac MRI is currently the clinical standard for following patients after TOF repair to assess the severity of PR and PA stenosis as well as grade the degree of RV dilation and dysfunction. Recently developed 4D flow imaging techniques [1,2] have simplified the flow quantification by permitting *post priori* quantification of vessels of interest in any imaging plane and allow for the visualization of complex flow patterns, which may be equally important in determining functional outcomes following surgery for complex congenital heart disease. The purpose of this study was to compare the flow patterns obtained with a 4D flow technique (PC VIPR) in the right atrium and ventricle in patients with TOF to those in normal volunteers.
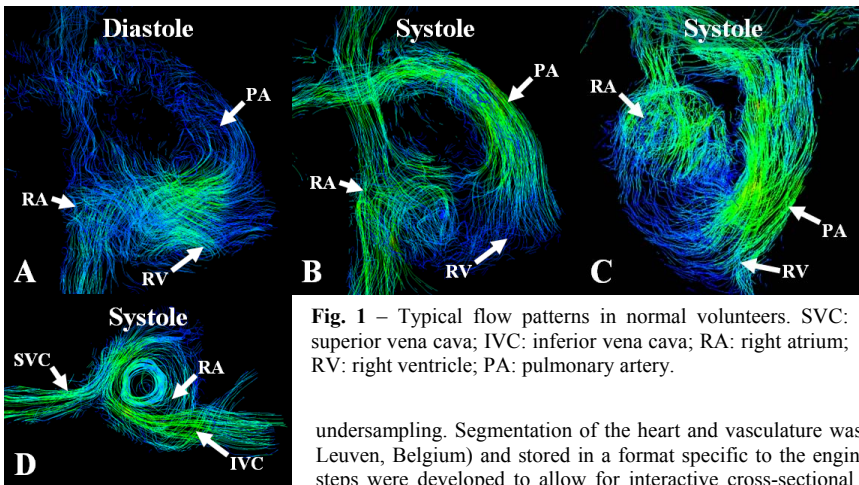

Fig. 1 – Typical flow patterns in normal volunteers. SVC: superior vena cava; IVC: inferior vena cava; RA: right atrium; RV: right ventricle; PA: pulmonary artery.

Methods: After obtaining subject consent according to our IRB-approved protocol, MRI studies were performed in 10 patients with TOF (5M/5F; 20.6±12.9 years) and 10 normal volunteers (6M/4F; 33.9±13.1 years). Examinations were performed on 1.5T and 3.0T clinical systems (GE Healthcare, Waukesha, WI). All data were acquired with a radially undersampled PC trajectory, PC VIPR (Phase Contrast Vastly undersampled Isotropic Projection Reconstruction) [2]: imaging volume = 320 x 320 x 320 mm^3, readout = 256-320, 1.0-1.25 mm^3 acquired isotropic spatial resolution, and VENC of 50-200 cm/s. Respiratory gating was performed with an adaptive gating scheme based on bellows readings, resulting in a scan time of approx 10 minutes with 50% respiratory gating efficiency. To reliably achieve high quality images, several correction schemes were applied to account for the effects of T_1-saturation, trajectory errors, motion, and aliasing associated with undersampling. Segmentation of the heart and vasculature was achieved with an image processing software (Mimics Materialise, Leuven, Belgium) and stored in a format specific to the engineering visualization software Ensight (CEI, Apex, NC). Processing steps were developed to allow for interactive cross-sectional analysis for velocities and flow rates in volumetric cine datasets. Interactive streamline and particle tracing visualizations of the superior vena cava (SVC), inferior vena cava (IVC), right atrium (RA), RV, and PA were reviewed by two experts in cardiac imaging to characterize flow patterns in the right atrium and ventricle. In the patients with TOF, RV function was quantified using ECG-gated CINE balanced SSFP and the severity of PR was calculated using 2D PC. Quantification of RV function and PR were performed using CV Mass and Flow Analysis software package in an Advantage Workstation (version 4.2, GE Heltcare, Waukesha, WI).

Results: RV ejection fraction in TOF patients was within normal limits, 53.4% ± 6.9% (normal 40-60). RV end-diastolic and end-systolic indices in TOF patients were elevated, 120.7±50.9 mL/m^2 (normal: 62-88) and 55.7±27.0 mL/m^2 (normal: 19-30), respectively. PR (range: 5-56%) was present in 7/10 TOF subjects and was correctly identified in all subjects using PCVIPR. Typical flow patterns in normal volunteers and TOF patients are shown in Figures 1 and 2, respectively. Distinct systolic ("S") and diastolic ("D") peaks are observed in the SVC and IVC. In normal volunteers, the S-wave predominates while in TOF patients, the D wave predominates (Fig. 3). Filling of the RV in normal volunteers is smooth and uniform with majority of flow directed toward RV outflow tract while in patients with TOF, the RV inflow is marked by larger vortices and flow directed toward the RV apex, especially in patients with PR.
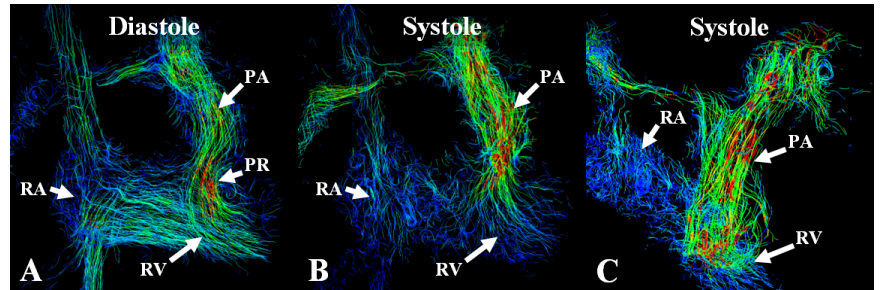

Fig. 2 – Typical flow patterns observed in patients with TOF. SVC: superior vena cava; IVC: inferior vena cava; RA: right atrium; RV: right ventricle; PA: pulmonary artery; PR: pulmonary regurgitation.

Conclusion: Flow patterns in the RA and RV of normal volunteers are very uniform and well organized, following patterns that have been described previously [3]. Interestingly, RA and RV flow patterns in patients with TOF are dramatically different from those in normal volunteers and may help explain the increased symptoms during exercise in the repaired heart. Given the small number of subjects and the variability in types of repairs performed, it is not possible to determine the relationship between types of repair and affect on RA and RV flow, but will be the subject of continued investigation.

References: [1] M Markl, et al. J Comput Assist Tomogr 2004; 28: 459. [2] T Gu et al., AJNR 2005; 26, 743. [3] PJ Kilner, et al. Nature 2000; 404: 759.
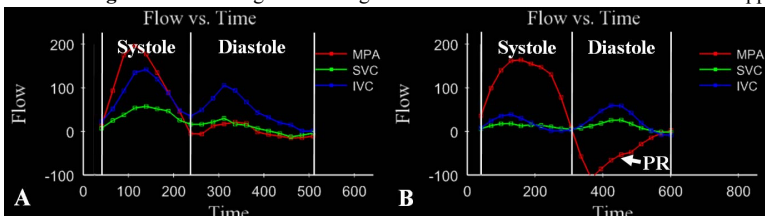
Fig. 3 – Typical flow-time curves in superior vena cava (SVC), inferior vena cava (IVC) and main pulmonary artery (MPA) for normal volunteers (A) and patients with TOF (B). Flow into right atrium from SVC and IVC occurred primarily during diastole. Pulmonary regurgitation (PR) was present in 7/10 patients with TOF.