

# Whole heart flow-sensitive 4D MRI in patients after repair of tetralogy of Fallot

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**Introduction:** Tetralogy of Fallot (TOF) is the most common cyanotic congenital heart defect and accounts for about 10% of all congenital heart diseases [1]. Pulmonary valve insufficiency with consecutive right ventricular volume overload is the most serious long-term postoperative problem [2]. MRI has become the method of choice for evaluating cardiovascular function after surgery for TOF [3]. Standard MRI protocols, however, provide neither a complete picture nor detailed information about 3D hemodynamics and flow alterations occurring in the right ventricular outflow tract and the entire pulmonary vascular system at different points in time. The purpose of this study was to employ flow-sensitive 4D MRI for the analysis of flow characteristics in patients after repair of TOF, particularly with respect to changes in the pulmonary system and their correlation with pulmonary vascular geometry.

**Methods:** Measurements were performed in ten patients (age  $12.1 \pm 8.1$  years, range 2–24 years) and four healthy controls (age  $26 \pm 0.8$  years, range 25–27 years) on a 1.5T and 3T MR system (Avanto & Trio, Siemens, Germany). The MRI protocol consisted of a time-resolved contrast-enhanced MR angiography (CE-MRA) (TE=1.0, TR=2.5, FA 25°, spatial resolution ~1.3mm<sup>3</sup>, temporal resolution=2.2–4.9s) and k-space segmented rf-spoiled gradient echo sequence with interleaved 3-dir. velocity encoding (velocity sensitivity=150–200cm/s, TE=2.4, TR=4.9, FOV=125–345x250–460, spatial resolution=1.7–4x1.84–3.16x1.56–2.5mm<sup>3</sup>, temporal resolution ~38ms, FA 7–15°, scan time ~10–20 min). Flow-sensitive 4D-MRI acquisitions were synchronized to the heart rate and breathing using prospective ECG-gating and adaptive diaphragm navigator gating [4]. Data analysis included the calculation of a 3D phase contrast (PC) MR angiogram from the 4D MR data which was combined with 3D blood flow visualization (EnSight v. 8.2, CEI, Apex, NC, USA). Visualization of postoperatively altered pulmonary flow was achieved by 3D virtual particle traces [5] which were emitted from planes in the ascending aorta (AAo), main pulmonary artery (TP), right and left pulmonary artery (rPA/IPA). Geometric measurements of the pulmonary angles and diameters were performed in MIPs of the CE-MRA. Flow pattern visualization was analyzed using a 3-grade ranking (0–2) with regard to vortex severity, retrograde flow and flow acceleration in the pulmonary system and the aorta. Blood flow quantification included flow-time curves, total flow and systolic peak velocities at the corresponding planes. A linear regression correlation analysis was employed to evaluate the correlation of vessel geometry and hemodynamics.

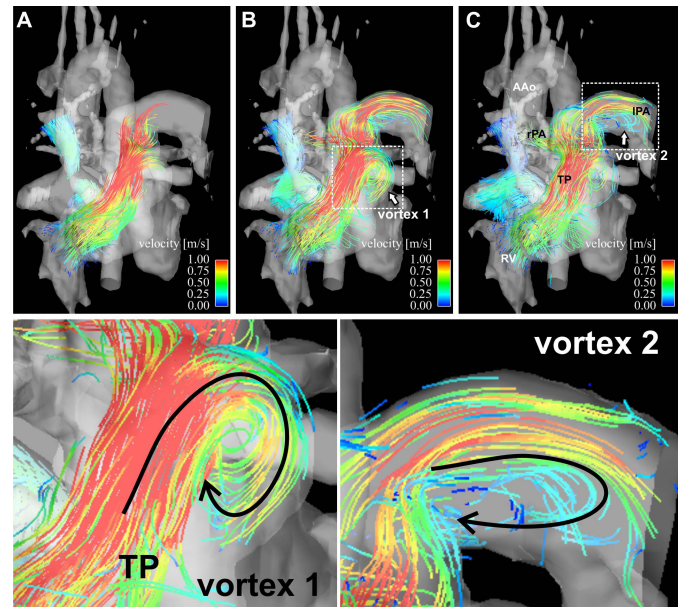
**Results:** 4D blood flow acquisitions, subsequent visualization and quantification were successful in all individuals. We observed a marked variation in flow characteristics in all the patients. Mean vortex severity in the TP was  $0.9 \pm 1.0$  in patients, with less severe vortices in the rPA ( $0.2 \pm 0.7$ ) and IPA ( $0.7 \pm 0.9$ ). High peak velocities >1.5m/s in the TP were apparent in eight patients (average grading =  $0.8 \pm 0.4$ ) and in the rPA and IPA in seven and six patients, respectively (Fig 1). All patients presented unmistakable retrograde flow in the TP due to pulmonary insufficiency (average grading =  $1.8 \pm 0.4$ ) (Fig.3). Flow acceleration, vortices and retrograde flow were not detected in the healthy volunteer group.

TOF patients revealed a significantly smaller angle between the TP and IPA (angle  $\beta$ ) and a larger angle between the rPA and IPA (angle  $\gamma$ ). Systolic peak velocity in the TP was significantly higher in patients ( $1.9\text{m/s} \pm 0.7\text{m/s}$ ) than controls ( $0.9\text{m/s} \pm 0.1\text{m/s}$ ), Fig.2A. Regurgitation fraction in patients was  $29\% \pm 11\%$ , whereas no regurgitation was measured in controls. There was consistently higher blood flow in the rPA of the TOF patients (rPA/IPA flow ratio:  $2.6 \pm 2.5$  vs.  $1.1 \pm 0.1$  in controls, Fig. 2B, 3). We detected significant correlations between vortex severity and pulmonary vessel size ( $r=0.71$ – $0.79$ ) and between flow regurgitation in the rPA and the branching angles of the main pulmonary artery: angle  $\beta$  ( $r=-0.59$ ), angle  $\gamma$  ( $r=0.73$ ).

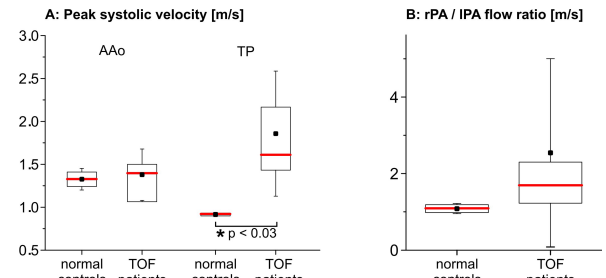
**Discussion:** 4D MR flow analysis revealed abnormal flow patterns in the entire group of TOF patients, which correlated significantly to vascular geometry. Compared to healthy controls, the different angles between the pulmonary arteries in TOF patients had a major impact on pulmonary retrograde flow and flow ratios. We detected a close correlation between the pulmonary arteries' diameter and vortex appearance which may lead to ineffective antegrade flow and vascular dilation. Beyond its unique potential to demonstrate the complexity of vascular morphology and function in TOF patients, 4D MR flow analysis may prove valuable in clinical routine by providing important data for therapy and for improving the monitoring of patients with TOF.

**References:** 1. Therrien J, et al. Lancet 2003; 362:1305–13 2. Huehnergarth KV, et al. Heart 2008; 94: 1663–1669. 3. Kilner PJ, et al. Eur Heart J 2010; 31:794–805. 4. Markl M, et al. JMRI 2007; 25(4):824–831 5. Buoncore MH. MRM 1998; 40:210–226.

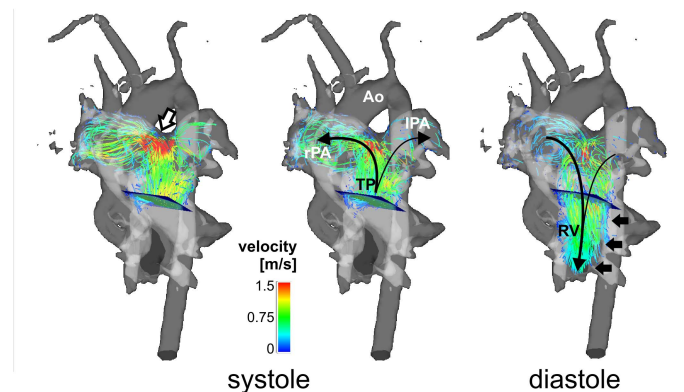
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**Fig. 1: Top row:** 3D particle trace visualization for 3 systolic time-frames (A-C) illustrates high systolic velocities (red color) and vortex formation (arrows) in the pulmonary trunk (TP) and left pulmonary artery (IPA). Coincidence of severe vortex flow (grading 2) and enlargement of the TP. **Lower row:** Magnification of vortex flow in TP and IPA (vortex 1 and 2).



**Fig. 2: A:** Comparison of peak systolic blood flow velocities in ascending aorta (AAo) and pulmonary trunk (TP) and **B:** flow ratio to the left (IPA) and right pulmonary arteries (rPA) between TOF patients and controls.



**Fig. 3:** Evolution of blood flow in the TP and pulmonary arteries visualized by 3D particle traces originating from an emitter plane at the level of the pulmonary valve. Substantial flow acceleration ( $v > 1.5\text{m/s}$ ) during systole is clearly evident (white arrow). Pulmonary valve insufficiency resulted in substantial diastolic retrograde flow (small black arrows). Marked asymmetry of flow to and from the left (IPA) compared to the right (rPA) pulmonary artery was detected (highest rPA/IPA flow ratio = 8.2 in the study cohort).