

Whole Heart 4D Hemodynamics in Patients with Transposition of the Great Arteries after Switch Procedure

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Introduction: In d-TGA (dextro-transposition of the great arteries), one of the most frequent cyanotic congenital heart defects, the aorta and main pulmonary artery are transposed [1]. Patients often suffer from pulmonary arteries' stenosis, aortic root dilatation or valve insufficiencies after the corrective arterial switch procedure [2,3]. Standard MRI methods or echocardiography can depict the abnormal geometry of the cardiovascular system in TGA-patients after repair but they are limited in analyzing hemodynamic alterations, particularly in evaluating the pulmonary arteries [4]. For identification of occurring postoperative complications and a better understanding of the complex hemodynamics and their correlation with pulmonary trunk (TP) location, we employed whole heart flow-sensitive 4D MRI in TGA patients and compared them with controls.

Methods: Whole heart flow-sensitive MRI was performed in 9 patients after repair of TGA (mean age = 12.2 ± 5.7 years, 2 female) and 4 healthy volunteers (13.9 ± 2.8 years) examined on 1.5T and 3T systems (Avanto and Trio, Siemens, Germany). The patients were divided into two groups regarding the TP location: 6 had an anterior central location to the ascending aorta (AAo), 3 an anterior right-sided position. Measurements were performed during free breathing using prospective ECG gating and adaptive diaphragm navigator gating for respiration control. Flow-sensitive 4D MRI was based on a k-space segmented rf-spoiled 3D phase contrast gradient echo sequence with 3D velocity encoding ($v_{enc} = 150-200\text{cm/s}$, $TE/TR = 2.4\text{ms}/4.8\text{ms}$, $FA = 7-15^\circ$, $FOV = 320 \times 240\text{mm}^2$, spatial resolution = $2.5 \times 2.5 \times 2.8\text{mm}^3$, temporal resolution = 38.4ms , scan time $\sim 10-20\text{min}$) [5]. The normal and postoperative altered hemodynamics in volunteers and TGA patients were visualized (EnSight, CEI, Apex, NC, USA) using the 3D PC-MRA in combination with systolic stream-lines or time-resolved 3D particle traces released from planes at the level of the aortic and pulmonary valve, the right and left pulmonary arteries (rPA, IPA). 3D visualization was analyzed regarding the presence of local flow acceleration (peak velocities $> 1.5\text{m/s}$) and the severity of vortex flow which was graded in 3 categories (0-2). The same planes were used to quantify flow-time curves and peak systolic velocities from the 4D data. Continuous variables were compared using an unpaired tow-sided t-test. All tests used a significance level of 5%.

Results, 3D visualization: As illustrated in figure 1, 3D flow pattern grading revealed similar flow characteristics in the aorta of TGA patients and controls despite slight aortic root dilatation in 8 patients. Substantial hemodynamic differences were found in the pulmonary system. Flow acceleration with regional velocities $> 1.5\text{m/s}$ in the TP, IPA and rPA was clearly visible in all TGA patients as seen in figure 1 but absent from all volunteers. A higher incidence of flow vortex formation was observed in the TP in TGA patients (6 patients, grading = 0.8 ± 0.7) compared to normal volunteers (no vortex flow). Noticeably, vortex flow was only seen in patients with a central TP location while no vortex flow was detected in all 3 patients with a right-sided location.

Flow quantification: Blood flow and peak systolic velocities in the ascending aorta were similar for volunteers and patients, as summarized in figure 2 and table 1. Pulmonary flow was substantially altered and the rPA/IPA flow ratio was more variable and higher (not significant) in TGA patients compared to controls. Consistent with the results from 3D flow visualization, quantification of peak velocities in the pulmonary system revealed a more than two-fold (120%) and significantly ($p < 0.05$) increase in TGA patients compared to volunteers (table 1).

Discussion: Postsurgical blood flow alterations in TGA patients after switch procedure were clearly visualized by 4D MRI. Compared to healthy volunteers, significantly increased peak velocities in the pulmonary trunk and arteries were measured without the presence of vessel stenosis. We detected a correlation between the TP position located directly anterior to the ascending aorta or slightly shifted to the right and the vortex flow appearance. Although the number of examined patients is limited, our first results hint at a geometrical influence of an unfavourable central TP position provoking disturbed pulmonary blood flow. 4D flow analysis is the ideal technique for evaluating vascular morphology and hemodynamics in the follow-up diagnostics of TGA patients and revealed to date unknown postsurgical flow mechanisms.

References: 1. Warnes CA, et al. Circ. 2006; 114(24):2699-709 2. Freedom RM, et al. Circ. 2000; 102:IV58-IV68 3. Hutter PA, et al. JTCs 2002; 124:790-7 4. Cohen MD, et al. AJR 2010; 191(1):250-60 5. Markl M, et al. JMRI 2007; 25:824-831.

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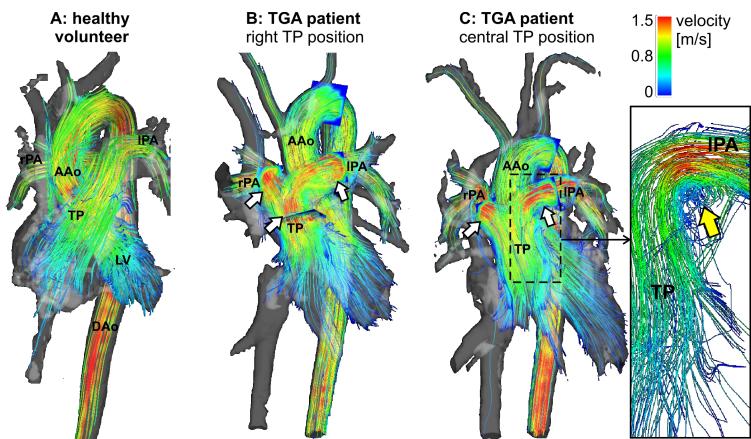


Fig. 1: 3D blood flow characteristics (systolic 3D stream lines, $t_{ECG} = 172\text{ms}$) in two TGA-patients after switch procedure (B and C) compared to a healthy volunteer (A). The surgically altered geometry of the great vessels after TGA is clearly visualized. For TGA patients, the pulmonary trunk (TP) is completely located anterior to the ascending aorta (AAo) resulting in an altered route of the left (IPA) and right (rPA) pulmonary artery compared to the healthy volunteer. The modified geometry resulted in substantially altered hemodynamics and particularly flow acceleration in the pulmonary system (white arrows). Differences in the surgical technique, i.e. different positions of the pulmonary trunk (B versus C), resulted in increased incidence of secondary flow patterns (flow vortex, right, yellow arrow, grading = 1) for patients with a central position of the TP.

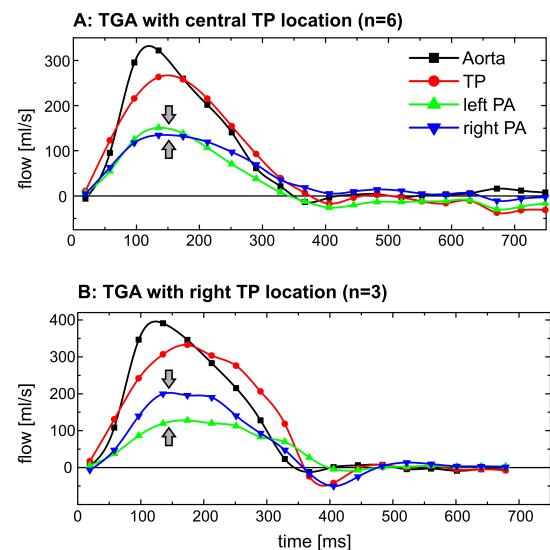


Fig. 2: Temporal evolution of blood flow in the aorta, pulmonary trunk (TP) and left and right pulmonary arteries for patients with central (A) and right (B) TP location. Note the increased differences in systolic blood flow to the left and right lungs (gray arrows) for the right compared to the TP central position.

	peak systolic velocity Ao	peak systolic velocity TP	rPA / IPA flow ratio
TGA patients (n=9)	1.40 ± 0.15	2.03 ± 0.82	1.6 ± 0.9
healthy controls (n=4)	1.33 ± 0.13	0.92 ± 0.03	1.1 ± 0.1
t-test (p-value)	0.39	0.02	0.25

Table 1: Descriptive statistics of flow quantification in the ascending aorta (AAo), pulmonary trunk (TP), and left and right pulmonary (IPA, rPA) arteries.