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Zhong, L., Schrauben, E.M., Garcia, J. et al. (13 more authors) (2019) Intracardiac 4D flow MRI in congenital heart disease : recommendations on behalf of the ISMRM flow & motion study group. Journal of Magnetic Resonance Imaging, 50 (3). ISSN 1053-1807

https://doi.org/10.1002/jmri.26893

Introduction:

Survival improvement in patients with congenital heart disease (CHD) has led to a growing number of adults living with CHD.

4D flow MRI has been used for the evaluation of various challenging CHD types. Quantitative measures of flow perturbations using 4D flow can aid in surveillance and treatment decision-making, and have been shown to be similar to standard clinical 2D PC MRI with acceptable test-retest repeatability [1-5]. Using 4D flow, it is possible to assess flow volume in large thoracic vessels, comprising the pulmonary-systemic shunt ratio (Qp/Qs), shunt flow, peak flow, valvular regurgitant flow, and collateral flow volumes. Intracardiac flow patterns, including flow connectivity and distribution, pressure gradients, vortex/helical flow patterns, directionality, and turbulent and laminar energy losses, can also be assessed.

The aim of these recommendations from the ISMRM Flow & Motion Study Group is to standardize 4D flow in CHD with recommended acquisition, reconstruction, and post-processing. This document focuses on CHD assessment with 4D flow, which requires for example coverage of a large volume in the thorax, and a wide range of velocities. Details on aortic 4D flow acquisitions can be found in the 2015 4D flow consensus statement [2].

Acquisition and reconstruction:

In 4D flow, time-resolved 3D blood dynamics over the entire cardiac cycle are measured by velocity encoding applied in three orthogonal directions with prospective or retrospective electrocardiogram (ECG) gating. A 3D volume is acquired covering the whole heart and large thoracic vessels in typical transverse, sagittal or coronal orientations (**Figure 1 – A**). Alternatively, a quasi-3-chamber view may be used to include the top of aortic arch in the same scan**.** Imaging acceleration strategies, such as parallel imaging with a factor of 2 to 3 for both phase- and slice-encoding directions can be used to accommodate a free breathing scan. Ideally,

valve-tracking should be performed directly on 4D flow magnitude images. Alternatively multiple 2D bSSFP cine, 3D MRA (contrast-enhanced or bSSFP) or 3D cine bSSFP MRI acquired in multiple views provide the anatomical reference for 4D flow analysis. For such combined data analysis, images must be spatially and temporally aligned to the 4D flow acquisition.

Table 1 lists important imaging parameters and their recommended settings, which should be detailed in reports. These are based on the JCMR consensus document [2] and current consensus. They do not preclude additional specialized measurements in individual patients. Some considerations:

- Resolution: Acquired voxel size according to JCMR consensus document [2] for intracardiac flow is 3 mm isotropic or less. This is considered coarse for valvular flow. We are updating towards 2.5 mm isotropic. This value may be updated depending on the size of the structure imaged – accurate quantification should include a diameter of at least 5 voxels.
- Acceleration: Use of parallel imaging is preferred. Consider using segmented TFE up to TFE factor of 2.
- EPI: The longer TE in EPI acquisitions results in displacement artifacts and turbulence induced intra-voxel phase dispersion, and should thus be avoided in stenotic flows.
- Respiratory gating: Previous studies have demonstrated reasonably accurate flow volume quantification in large vessels and for intracardiac flow [6] without compensation for respiratory motion. However, respiration motion may result in blurring, which affects small structures and areas with large velocity variations like shunts, regurgitant and stenotic jets. Respiratory motion larger than the acquired spatial resolution should therefore be compensated [2].

- VENC: If no stenosis is present, VENC of 120-150 cm/s is sufficient. In case of stenosis, anticipate to adapt to ⩾ 200 cm/s. Use post-processing tools that will perform anti-aliasing and phase offset correction. Also consider using through-plane motion correction of the annulus for accurately assessing transvalvular flow. Recently developed research strategies using dual- and multi-VENC acquisitions show promise in alleviating the issues from large patient-specific velocity ranges [7].
- Cardiac gating: Retrospective gating is preferred, especially for intracardiac applications to allow analysis of both systole and diastole. Prospective gating is suitable for applications when systole (e.g. aortic assessment) is the main interest.

Post-processing and visualization:

Angiography visualization: A time-averaged or time-resolved 3D phase-contrast MR angiography (PC-MRA) can be computed directly from 4D flow from a combination of velocity and magnitude data.

Flow visualization: Visualization of blood flow can be displayed in two or three-dimensions using velocity vectors, particle traces, or streamlines (**Figure 2 – A-D**).

Velocity vector display: The magnitude and direction of flow can be depicted using arrows of voxel-wise velocity vectors, which can be sized and color-coded based on blood speed. A velocity vector display in a 2D plane can be useful for qualitative assessment of cardiac inflow and outflow, stenotic jet direction, and regions of recirculating flow.

Particle trace display: Flow connectivity and distribution can be visualized and quantified using 3D pathlines from emitted particles, which reflect the temporal trajectory of blood..

Streamline display: Streamlines are instantaneous curved lines tangential to the velocity direction. Streamlines in a 2D plane or 3D volume can be helpful to display the inflow and outflow directions for identifying regions of flow recirculation.

Jet detection and visualization: Shunts, insufficient valves, and valvular and vascular stenoses result in jet flow which can be detected in the 4D flow dataset by volume rendering of high velocities [8] or visualization of turbulent intensity [9].

Flow volume quantification: The volumetric coverage of 4D flow offers retrospective positioning of planes for flow volume measurements at any location within the acquired volume (**Fig. 1 – B-D**). Analysis planes should preferably be placed perpendicular to the vessel of interest. These planes can be at a fixed position over the cardiac cycle for vascular flow where vessel motion is minimal over the cardiac cycle. For valvular flow a fixed plane can be used when only the total flow is considered. For assessment of regurgitant flow in the mitral or pulmonary valve and other valves, as well as quantification of shunt flow in VSD or ASD, retrospective valve tracking is recommended [10] (**Figure 2 – E-H**). Advanced 4D flow metrics (volumetric energetics and flow patterns) are listed in **Table 2**.

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Table 1: Acquisition of intra-cardiac 4D flow MRI in CHD

	Recommendation	Consideration
Pulse sequence	Velocity-encoded phase-contrast spoiled gradient-echo-based	T1 turbo-field echo (TFE), Philips fast spoiled gradient echo (FSPGR), GE RF-spoiled gradient echo (GRE), Siemens
Field of view (FOV)	340×340 mm^2	Large enough to cover the whole heart as well as aortic root
Slab/slice orientation	Transversal or quasi-3 chamber-view	Transversal: easy planning, least demand on gradient performance avoiding potential errors induced by system imperfections Quasi-3-chamber view: potential coverage of aortic arch in the same scan
Spatial resolution (voxel size)	2.5-3.0×2.5-3.0×2.5-3.0 mm^3	Isotropically acquired voxel preferred Optional: interpolation of reconstructed voxel size to, e.g. 1.5×1.5×1.5 mm^3
Echo time (TE)	Shortest	To minimize unwanted dephasing due to, e.g. turbulence, B0 field inhomogeneities, etc.
Repetition time (TR)	Shortest	For short scan time
Flip angle	10° w/o contrast 15° w/ contrast	Ernst angle preferred ideally: $\alpha = \text{acos}(e^{-TR/T1})$
Partial k-space sampling		
Partial echo	no	Not preferred to avoid calculation errors
Partial Fourier / scan (phase- or slice-encoding direction)	0.75 to 0.8	Compromise between scan time, SNR, and potential errors introduced by phase errors or artifacts
Parallel imaging (phase- and slice-encoding directions)	2 to 4	Compromise between scan time, SNR, and potential errors introduced by phase errors or artifacts
Partial cardiac phase	No	No view sharing across cardiac cycles, i.e. 100% cardiac phase percentage, preferred
Temporal resolution	40 ms	Absolute resolution is calculated as Segments x NSA x TR To resolve cardiac motion adequately
Cardiac phases	≥ 30	Reconstructed phases For visualization purpose
VENC	Individually adjusted	Recommend single VENC values of 120 to 150 cm/s in the absence of stenosis
Motion compensation		
Cardiac	Retrospective ECG gating	Prospective gating not preferred due to incomplete temporal coverage of the cardiac cycle
Respiratory	No	Current compromise between scan time and breathing artifacts Alternative: respiratory triggering or navigator at diaphragm with prolonged scan times
NSA	1	Current compromise between scan time, SNR and breathing artifacts
Scan Time	< 10 min	Patient tolerance

Table 2: Summary of conventional and advanced 4D flow parameters in number of congenital heart diseases

Region	CHD type	Conventional flow parameters	Advanced flow parameters
Venous return	Fontan/Single Ventricle	Collateral flow volume, peak flow, valvular flow volumes	Kinetic energy loss index, energy losses, flow connectivity distribution
	Tetralogy of Fallot	Right heart (RA, RV, PA) systolic peak velocity, Net flow volumes , retrograde flow	Wall shear stress, vorticity
Heart wall	atrial(-ventricular) septal defects	Shunt flow volume, collateral flow volume, Qp/Qs ratio	3D vortex flow, kinetic energy, viscous energy losses, turbulent energy losses
Aortic valve	Bicuspid aortic valve	Net flow volume, regurgitation flow volume, peak flow	Wall shear stress, turbulent losses, viscous energy losses, volumetric pressure gradients, helicity
	Marfan syndrome	AV Peak flow, AV flow volumes	Wall shear stress, vortex/helical flow grading
Outflow tracts	dextro transposition of the great arteries	Net flow volumes, flow ratio, peak velocity	Wall shear stress, grading of vortical and helical flow
	Aortic coarctation	collateral flow volume, peak flow at the coarctation level	volumetric pressure gradients, turbulent energy losses, wall shear stress

Figure Legends:

Figure 1: A – Volumetric planning of intra-cardiac 4D flow MRI in a conventional transversal orientation. Note other orientations can be prescribed (e.g. quasi-3-chamber) for coverage of extracardiac vessels. **B-D –** Example quantification using 4D flow in a 15 year-old male with tetralogy of Fallot post-stenting of right ventricle and pulmonary artery. For Qp/Qs measurement (**B**, aortic flow), pulmonary artery measurement was not possible due to the high turbulence from the stent. Here the flexibility of 4D flow MRI allows for retrospective assessment of Qp/Qs using measurements in the pulmonary arteries (**C**) or pulmonary veins (**D**).

Figure 2. **A-D –** Intracardiac 4D flow visualization example in a 16-year-old male with transposition of the great arteries following the arterial switch operation: (A) Contour in blue on the end-systolic angiographic image; (B) 3D-velocity vector display: The magnitude and direction of velocity can be visualized using small arrows or line segments indicating the local blood velocity direction and magnitude; (C) 3D particle trace display: Particles are emitted at end-diastole and follow the evolution of the velocity field throughout the cardiac cycle; (D) 3D streamline display: Streamlines are curved lines which are locally tangent to the velocity direction at an instantaneous timeframe. Both the particle traces and streamline display the characteristic anterior positioning of the pulmonary artery (yellow arrow) relative to the ascending aorta (white arrow) in the arterial switch procedure. **E-H –** Example valve tracking using 4D flow in a 10-year-old female with corrected atrioventricular septal defect, showing diastolic inflow (E, G) and systolic regurgitation (F, H) in the left atrioventricular valve. Tracking of valve displacement is performed on anatomical 2- and 4-chamber views (E, F), and jet tracking is visualized with velocity overlays (G, H; the purple plane is automatically angulated perpendicular to the flow velocity).