Flow quantification in the heart chambers: 3D PC-SSFP compared with spoiled GE

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Introduction: Flow quantification through the valves is of major importance in patients with valvular heart disease. Using a 3D MRI acquisition, the mitral valve can be imaged during the whole cardiac cycle, for direct quantification of flow through the valve. So far, 3D phase contrast (PC) for velocity quantification is only implemented in a spoiled Gradient Echo (GE) sequence. However, PC-GE has the disadvantage that the blood-myocardium contrast depends on inflow enhancement. For a 3D acquisition, the inflow enhancement is limited due to the large slab thickness, consequently after mitral valve closure the blood-myocardium contrast almost vanishes and accurate flow quantification is hampered. From theory it is known that SSFP is less inflow dependent than GE, and intrinsically has a better blood-myocardium contrast [1]. For these reasons we developed a 3D PC-SSFP sequence. It was already shown that the sequence had an improved blood-myocardium contrast [2]. Here we compare the flow quantification properties in comparison with 3D PC-GE.

Method: The 3D PC-SSFP sequence was based on a regular 3D SSFP gradient scheme with flow encoding as introduced in 2D by Overall et al. [3]. A bipolar flow-encoding pulse was placed on the slice-selection or read-out axis for through-plane and in-plane flow encoding respectively (Fig. 1). The 3D PC-SSFP sequence was implemented on a 1.5 Tesla scanner (Magnetom Sonata, Siemens, Erlangen, Germany). The sequence was tested using a constant-flow phantom with regular flow meters (Student's t-test). Mitral valves of twelve healthy volunteers were scanned with 3D PC-SSFP and 3D PC-GE in both long and short axis orientation, with 1D flow quantification through the valvular plane.

Imaging parameters were: voxel size 1.8x1.8x8 mm^3, matrix 192x128x8, FOV 340x226x64 mm^3, prospectively gated, Venc 150 cm/s. 3D PC-SSFP TR/TE 4.3/1.7 ms, 5 segments, flip angle 50º, BW 1532 Hz/pixel, duration 6 min. at 60 bpm. 3D PC-GE TR/TE 10.5/5.8 ms, flip angle 20º, BW 190 Hz/pixel, duration 15 min. at 60 bpm. For the PC-SSFP sequences a locally adjusted shim was applied. FOV was adapted to match subject geometry. Flow measurements were analyzed using commercial software (Mass, Medis, Leiden).

Mean and peak flow measurements through the descending aorta (visible in the long axis mitral valve images) were compared with 3D PC-GE measurements by Student's t-test. Flow measurements through the mitral valve by the two sequences were compared using Bland-Altman intra-observer analysis on mean and peak flow.

Results: Flow phantom measurements showed agreement with the flow meter data; data were consistent with the line of identity (linear regression: slope 1.05 p=0.1, offset 0.03 m/s p=0.1). Mean and peak flow through the descending aorta were compared between 3D PC-SSFP and 3D PC-GE. Both measures correlated well (mean flow r^2=0.79 and peak flow r^2=0.93), but mean flow showed a small significant bias of 0.91 cm/s (p=0.02).

Images resulting from the new 3D PC-SSFP sequence are shown in Figure 2. 3D PC-SSFP magnitude images had better contrast than 3D PC-GE [2]. The phase maps of 3D PC-SSFP showed more and stronger noise around the heart compared with 3D PC-GE. This was due to the lower SNR of muscle tissue and the steady-state related implementation of the velocity encoding [3] using half as low bipolar gradients.

Linear regression of flow through the mitral valve showed no significant difference from the line of identity. However mean flow showed poor correlation between 3D PC-SSFP and 3D PC-GE; correlation in short axis was r^2=0.54 and in long axis r^2=0.55. In contrast to mean flow, peak flow had a good correlation; r^2=0.96 and r^2=0.78, for short and long axis respectively. A Bland-Altman analysis on the repeatability of intra-observer flow results showed that 3D PC-GE always had larger limits of repeatability than 3D PC-SSFP, see Figure 3.

Discussion: This study shows the feasibility of flow quantification with a 3D SSFP sequence. *In vitro* flow measurements matched well with the regular flow meters and with 3D PC-GE measurements. *In vivo* there was a small but significant bias with 3D PC-GE, the cause of this difference needs further investigation. Mitral valve peak flow measurements showed good correlation with 3D PC-GE, mean flow showed only moderate correlation. However, correlation in the descending aorta was good, and repeatability of 3D PC-SSFP was better than 3D PC-GE. The higher contrast-to-noise ratio within the heart chambers supported better positioning of the ROI at the mitral valve level. Using the PC-SSFP approach, higher SNR and CNR and more reliable flow quantification provide improved cardiac flow imaging. Working towards mitral valve regurgitation quantification, a full 7D acquisition, retrospective triggering, and scan time reduction using parallel imaging techniques are further required.

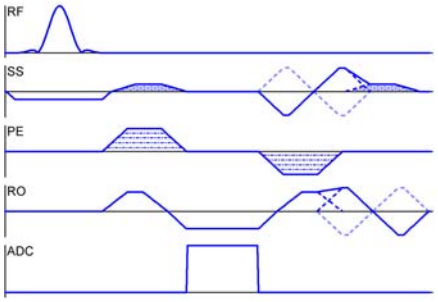

Figure 1: The 3D PC-SSFP sequence. The bipolar gradient for velocity encoding is placed after read-out on the slice-select or read-out axis.

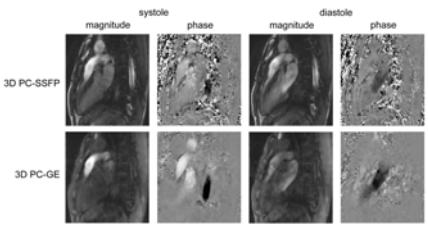

Figure 2: Typical 3D PC-SSFP and 3D PC-GE long axis images of the left atrium and ventricle (slice 4 of 8), in mid-systole (200ms after R peak) and at peak inflow in diastole (450ms after R peak). 3D PC-SSFP magnitude images show better contrast than 3D PC-GE, phase images show more and stronger noise due to the low SNR of muscle tissue and the steady-state related implementation of the velocity encoding.

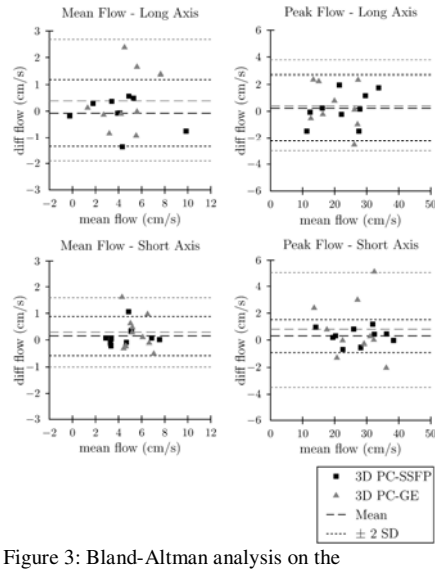

Figure 3: Bland-Altman analysis on the repeatability of intra-observer flow measurements. In all cases the repeatability of mean and peak flow in long and short axis orientation was lower in 3D PC-GE than in 3D PC-SSFP.

References: 1. Barkhausen J et al. Radiology 2001;219:264-269. 2. Rolf MP et al. ESMRMB 2008;644 3. Overall WR et al. MRM 2002;48:890-898.