Effects of Temporal Resolution and Velocity Encoding Strategies on Aortic Flow Measurement with Two-Dimensional Phase-Contrast MRI

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Introduction: Two-dimensional (2D) time-resolved (CINE) phase-contrast MRI (PC-MRI) with through-plane velocity encoding has been routinely used to measure blood flow in the aorta and pulmonary arteries.[1] Velocity measurements with single-directional velocity encoding can reliably quantify blood flow but may underestimate peak velocities since only one component of the 3D blood flow velocity vector is measured, particularly if the 2D imaging slice is not properly positioned. Three-directional velocity encoding enables quantification of the full velocity vector in all three dimensions and thus is less sensitive to plane placement. However, interleaved three-directional velocity encoding requires additional velocity sensitive acquisitions and thus reduces temporal resolution which may result in temporal filtering and thus underestimation of peak flow and peak velocities.[2] The purpose of this study was to systematically investigate the effects of temporal resolution and different velocity encoding strategies on aortic flow quantification in healthy volunteers.

Table 1: Sequence parameters for 2D PC-MRI with single-directional through-plane, interleaved and sequential three-directional (3-dir.) velocity encoding.

Sequence Parameters	**Through-plane 1-dir.**	**Interleaved 3-dir.**	**Sequential 3-dir.**
TR/TE	4.7/2.4ms	4.8/2.5ms	4.8/2.5ms
Velocity Sensitivity	150cm/s	150cm/s	150cm/s
In-plane Resolution	$1.7\times2.0mm^2$	$1.7\times2.0mm^2$	$1.7\times2.0mm^2$
Slice Thickness	8mm	8mm	8mm
Temporal Resolution	28.0s	19.2s	4.8s
Flip Angle	30º	15º	15º
ECG Gating	Retrospective	Prospective	Prospective
Respiratory Control	Breath hold	Navigator	Navigator
Acquisition Time	~18s	~1min	~4min

Methods: 2D CINE PC-MRI in an axial plane orthogonal to the proximal ascending (AAo) and descending (DAo) aorta was performed in 15 healthy volunteers (7 female, age=44±16 years) on a 3T MRI scanner (Skyra, Siemens, Germany). For each subject, three 2D CINE PC-MRI sequences with different temporal resolution, velocity encoding schemes, and total scan times were used as shown in Figure 1. In addition to conventional breath-hold 2D CINE PC-MRI with single-directional through-plane (TP) velocity encoding (Fig. 1a), interleaved (Fig. 1b) and sequential (Fig. 1c) 3-directional velocity encoding data were acquired (see Table 1 for detailed imaging parameters). Thus, the minimum temporal resolution for single-directional TP, interleaved and sequential 3-directional velocity encoding was 2TR, 4TR and TR, respectively. All data were analyzed with customized software programmed in Matlab (The Mathworks, MA, USA) including pre-processing (noise masking and correction for velocity aliasing, eddy currents and Maxwell terms) and semi-automatic flow quantification as described previously.[3] Net flow and peak velocities in the AAo and DAo were calculated in manually delineated regions of interest. Pairwise comparisons of the flow parameters were performed between the three encoding schemes (paired t-test, $p<0.05$ was considered significantly different).

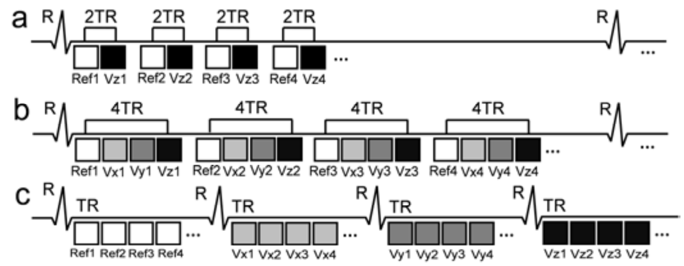

Fig. 1: Single-directional through-plane velocity encoding (a), interleaved 3-directional velocity encoding with a reference scan followed by three flow-sensitive scans in the *x*, *y* and *z* directions (b), and sequential 3-directional encoding where reference and three flow-sensitive scans are sequentially encoded in four consecutive cardiac cycles to improve temporal resolution (c).

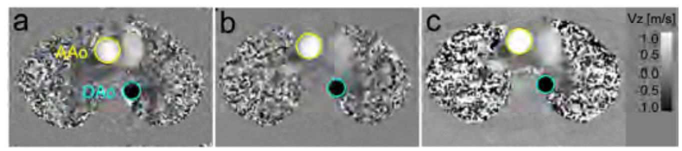

Fig. 2: Peak Systolic phase difference images (*Vz* component) of the aorta obtained using 2D CINE PC-MRI with single-directional through-plane (a), interleaved (b) and sequential (c) 3-directional velocity encoding, respectively.

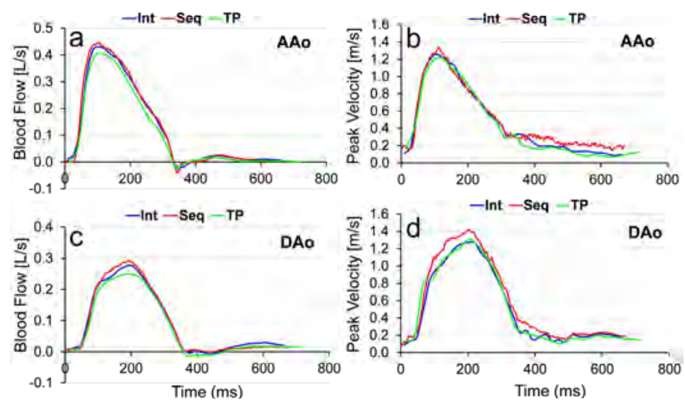

Fig. 3: Blood flow and peak velocity time-curves in the AAo (a, b) and DAo (c, d) for a 22-year-old male volunteer measured with through-plane (TP), interleaved (Int) and sequential (Seq) 3-directional velocity encoding.

Results: Figure 2 shows an example (22-year-old male volunteer) of the resulting systolic images for all three 2D CINE PC-MRI sequences. Similar phase difference images (through-plane direction) were obtained for single-directional TP (Fig. 2a), interleaved (Fig. 2b) and sequential (Fig. 2c) 3-directional velocity encoding. Figure 3 shows the corresponding time-resolved blood flow and peak velocity time-curves in the AAo (Fig. 3a and Fig. 3b) and DAo (Fig. 3c and Fig. 3d). In this case, sequential velocity encoding exhibited higher peak flow and peak velocity in both AAo and DAo compared with the other two encoding strategies. Figure 4 illustrates the net flow and peak velocity in the AAo and DAo measured with the three encoding schemes. Net flow in both AAo and DAo was not significantly different between the three encoding schemes (Fig. 4a). However, in comparison with single-directional through-plane velocity encoding, peak velocities in the AAo and DAo increased by 16.7% (P=0.007) and 4.9% (P=0.038) with interleaved 3-directional encoding and increased by 22.6% (P=0.002) and 12.2% (P=0.002) with sequential 3-directional encoding, respectively (Fig. 4b). In addition, peak velocities measured with sequential 3-directional velocity encoding increased by 5.1% (P=0.036) in the AAo and 7.0% (P=0.031) in the DAo compared with interleaved 3-directional velocity encoding (Fig. 4b).

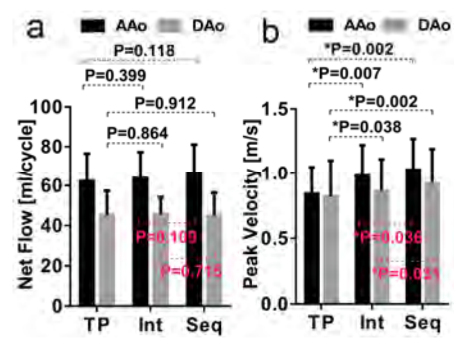

Fig. 4: Net flow (a) and peak velocities (b) in the AAo and DAo measured with single-directional through-plane (TP), interleaved (Int) and sequential (Seq) 3-directional velocity encoding.

Discussion: The results of this study demonstrated that high temporal resolution (e.g. ~5ms) may be required for accurately measuring peak velocities in the aorta. However, relatively low temporal resolution (e.g. ~20ms) can be used for aortic blood flow measurement because net flow was less sensitive to temporal resolution compared to peak velocities. In addition, aortic peak velocities were underestimated with single-directional through-plane velocity encoding compared to 3-directional velocity encoding schemes. It should be noted that sequential velocity encoding is currently limited by the long acquisition time, which needs to be shortened in combination with advanced acceleration techniques.[4]

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References: 1. Markl et al. *JMRI* 2012; 36:1015-1036. 2. Sala et al. *JCMR* 2014; 16:167. 3. Bock et al. *ISMRM* 2008; 16:3050. Jung et al. *JMRI* 2008; 28:1226-1232.