High temporal-resolution three-directional velocity measurements in a single breath-hold using EPI and direct inversion

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Introduction: Phase-contrast magnetic resonance imaging (PC-MRI) has become an important diagnostic tool used clinically to measure volume blood flow and peak velocities in major blood vessels and through heart valves. Using through-plane PC-MRI, the imaging plane must be prescribed exactly orthogonal to the direction of flow of interest; otherwise peak velocity can be severely underestimated. Multi-direction velocity encoding sequences, on the other hand, can accurately capture peak velocity independent of slice orientation and are therefore much less operator dependent [1]. Unfortunately, simultaneous encoding of all three directional velocity components (v_x, v_y, v_z) requires four encoding steps (including reference scan), twice the number of a single-directional sequence. This results in degradation of temporal resolution or increased scan time by a factor of two, eliminating the possibility of acquiring traditional ECG-triggered, segmented k-space, spoiled gradient-echo (GRE) data in a clinically feasible breath-hold. In this work, we present an echo-planar (EPI) implementation of balanced four-point velocity encoded PC-MRI for rapid, breath-hold acquisition of three-directional velocity data with high temporal resolution. This rapid acquisition approach is complimented by a novel direct inversion with regularized least square estimation of velocities from the acquired phase data to increase temporal resolution by a factor of four. The proposed technique enables simultaneous encoding of v_x, v_y, *and* v_z within a single 17 heart-beat breath-hold with an effective temporal resolution of 14.5 ms.

Methods: *Sequence:* The 2D EPI-PC sequence was implemented using the standard balanced four-point velocity encoding strategy [2]. Each velocity encoding step simultaneously encodes v_x, v_y, *and* v_z. From one encoding step to the next, the gradient first moments in two directions are altered by ΔM1. The EPI-PC sequence was implemented with echo-train-length 5, linear k-space reordering, and mono-polar readouts to reduce in-plane flow artifacts. A 15° rapid binomial water excitation pulse was used to provide fat suppression and high receiver bandwidth of 2000 Hz/pixel yielded a TE = 8.2 ms and TR = 14.5 ms. One velocity encoding combination was acquired per TR. A matrix = 192X144, resolution 1.7X1.7X10mm^3, and TGRAPPA acceleration rate 2, resulted in an acquisition time of 17 heartbeats, or about 15 seconds at a heart rate of 68 beats per minute.

Reconstruction: First, the series of magnitude and phase images was reconstructed using TGRAPPA. Then, direct inversion was used to estimate v_x, v_y, *and* v_z for each encoding on a pixel-by-pixel basis. In this method, instead of deriving a single estimate of v_x, v_y, *and* v_z from a set of four consecutive measurements, all measurements (the entire time series) were processed together using regularized least-squares, resulting in estimates of v_x, v_y, *and* v_z for every measurement and a factor of 4X improvement in temporal resolution, from 58 ms (4 x TR) to 14.5 ms (1 x TR). The regularization term was based on a finite difference approximation to the second-order temporal derivative operator [3].

Imaging: Experiments were conducted in five healthy volunteers using a clinical 1.5 T scanner (MAGNETOM Avanto, Siemens Healthcare, Erlangen, Germany) using body matrix and spine coils for signal reception. Scout images were used to locate the sagittal oblique, left anterior oblique candy cane view including the ascending, transverse, and descending aorta. Three-directional velocity measurements were made simultaneously in this imaging plane in a single breath-hold using the balanced four-point velocity encoded EPI-PC sequence. For comparison, images were acquired in the same view using the standard clinical ECG-triggered, segmented, spoiled GRE-PC sequence. To achieve adequate temporal resolution within a reasonable breath-hold with the GRE-PC sequence, three separate acquisitions were required, each encoding a different velocity direction. The GRE-PC sequence with single direction velocity encoding and five k-space lines per segment yielded a temporal resolution of 55 ms within a breath-hold of 17 heart beats.

Data analysis: Pixel-wise velocity magnitude (speed) maps were calculated as $\sqrt{v_x^2+v_y^2+v_z^2}$. ROIs were drawn on the aortic arch, descending aorta (DSA) and main pulmonary artery (MPA) to investigate velocities with major components in all three directions. Peak velocity and mean speed measurements within the ROIs were compared, and root-mean-square-error (RMSE) was measured between the speed curves obtained using the balanced four-point velocity encoded EPI-PC sequence and the reference standard GRE-PC. Linear interpolation was used prior to RMSE calculation to normalize effective frame rates.

Results: Representative magnitude (**Fig. 1a**), velocity maps in *x* (top-to-bottom) (**Fig. 1b**), *y* (left-to-right) (**Fig. 1c**), and *z* (through-plane) (**Fig. 1d**) directions, and speed map (**Fig. 1e**) of a systolic frame showing the entire thoracic aorta using the balanced four-point velocity encoded EPI-PC sequence from one volunteer are shown. Peak velocity curves for the aortic arch (**Fig. 1f**), DSA (**Fig. 1g**) and MPA (**Fig. 1h**) from the same volunteer acquired using the balanced four-point velocity encoded EPI PC method (red) and the GRE-PC reference standard (blue) are also shown. EPI-PC velocity curves have a temporal resolution of 14.5 ms, while the GRE-PC temporal resolution was 55 ms. Peak velocities measured using the balanced four-point EPI PC method were slightly, though not significantly (p = 0.07), higher than the those measured using GRE-PC, possibly due to the higher temporal resolution in the newly proposed method. No significant differences were observed between the mean speeds within all ROIs measured using the two methods (p = 0.11). Insignificant RMSE was observed in all ROIs showing a good correlation between the speed curves generated by the balanced four-point velocity encoded EPI PC and the reference standard.

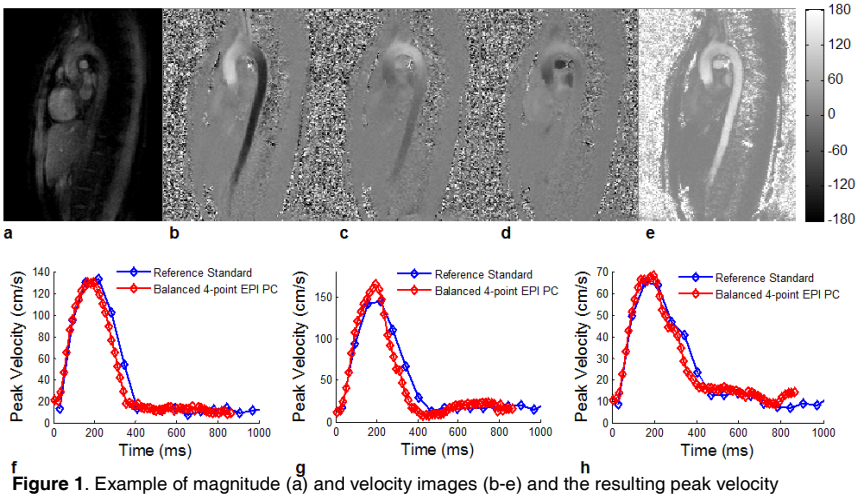

Figure 1. Example of magnitude (a) and velocity images (b-e) and the resulting peak velocity curves in the aortic arch (f), DSA (g) and MPA (h).

Conclusion: We have developed the novel balanced four-point velocity encoded EPI-PC method incorporating a novel direct inversion with regularized least square estimation of velocities from the acquired phase data. This combined approach provides simultaneous measurement of v_x, v_y, *and* v_z with an effective temporal resolution of 14.5 ms within a single breath hold, representing more than a factor of ten increase in efficiency over the standard GRE-PC approach. In the future, this approach can be applied to 7D flow imaging to dramatically reduce scan time.

References: [1] Sørensen et al. *Int J Cardiovasc Imaging* 2005, **21**:283-292. [2] Pelc et al. *JMRI.* 1991; 1(4):405-13. [3] Elden et al. *BIT.* 1977;17(2)134-45

Table 2. Peak velocities, mean magnitudes of velocities and RMSE of the balanced four-point velocity encoded EPI-PC with respect to conventional PC-MRI

ROI	Peak Velocity (Reference Standard)	Peak Velocity (Balanced 4-point EPI-PC)	Mean Speed (Reference Standard)	Mean Speed (Balanced 4-point EPI PC)	RMSE
Arch	92.8 ± 30.5 cm/s	96.9 ± 28.1 cm/s	24.5 ± 6.7 cm/s	23.3 ± 5.1 cm/s	4.8 ± 2.1 cm/s
DSA	115 ± 21.1 cm/s	120.1 ± 28.1 cm/s	33.1 ± 7.2 cm/s	29.3 ± 5.6 cm/s	6.8 ± 2.7 cm/s
MPA	77.8 ± 14.4 cm/s	78.2 ± 14.1 cm/s	26.9 ± 8.2 cm/s	24.2 ± 4.2 cm/s	5.9 ± 4.6 cm/s