Dual-Velocity Encoding Phase-Contrast MRI: extending the dynamic range and lowering the velocity to noise ratio

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TARGET AUDIENCE: This study explores the potential of measuring blood flow velocities using a dual-*venc* PC-MRI approach. This study will most interest method developers and clinical researchers who study blood flow measurements and derived parameters.

PURPOSE: For the detailed evaluation of cardiovascular flow, it would be desirable to gain quantitative information on both lower venous and high arterial blood flow velocities, which can differ by one order of magnitude even in normal subjects (10cm/s versus 150cm/s) [1]. Their acquisition with a single phase-contrast MRI (PC-MRI) acquisition is thus difficult and would result in either substantial velocity aliasing for high arterial blood flow or high noise levels for lower venous flow velocities. It was thus the aim of this study to perform low- and high-*venc* PC-MRI in a single measurement (dual-*venc*) to avoid aliasing and improve velocity to noise ratio (VNR ~ SNR_{mag}/*venc*). Previous studies have investigated dual-*venc* approaches based on post-processing methods [2], or have alternatively used five-point balanced flow encoding to reduce noise and aliasing in phase images [3], or velocity encoding was varied for acquiring data points during systole or diastole [4]. In this study, a fully integrated dual-*venc* sequence with a shared reference scan for improved scan efficiency was developed that allows the acquisition of both low- and high-*venc* data within a single acquisition. The resulting high-*venc* data can then be used for complete anti-aliasing of the low-*venc* data while maintaining the favourable VNR of the low-*venc* data. Dual-*venc* PC-MRI is thus expected to provide improved VNR without aliasing and improved quantification of the entire velocity spectrum (low to high). E.g. Low- and high *venc*s of 100cm/s and 200cm/s should thus result in a 200% VNR improvement. The aim of this study was to systematically test the performance of the dual-*venc* PC-MRI technique using a dedicated rotation phantom experiment.

METHODS: The dual-*venc* sequence was implemented as follows: the 1st gradient echo ($\Phi^{(ref)}$) was used to measure the reference (flow-compensated) phase similarly to the standard PC–MRI. In the following 6 TRs independent gradient waveforms for velocity encoding were used along the 3 orthogonal directions (i=x,y,z) with both low and high *venc* with optimized TE and TR [5]. This was achieved by efficiently distributing gradient moments between the reference scan ($M_{1i}^{(ref)}$, i=x,y,z), low ($M_{1i}^{(I)}$, i=x,y,z), and high ($M_{1i}^{(II)}$, i=x,y,z) *venc* based on the following boundary conditions:

$$venc_{I,i} = \frac{\pi}{\gamma \Delta M_{1i}^{(I)}} = \frac{\pi}{\gamma (M_{1i}^{(I)} - M_{1i}^{(ref)})} \quad \text{and} \quad venc_{II,i} = \frac{\pi}{\gamma \Delta M_{1i}^{(II)}} = \frac{\pi}{\gamma (M_{1i}^{(II)} - M_{1i}^{(ref)})} \quad i = x,y,z.$$ *TE and TR = minimal.*

Velocity encoding was determined by the duration and amplitudes of bipolar gradients ($G_i^{(ref)}$, $G_i^{(vencI)}$, $G_i^{(vencII)}$, j=I,II) the corresponding first order gradient moments $M_{1i}^{(j)}=\int G_i^{(j)} tdt$ (j=I,II). Blood flow velocities $v_{j,i}$ were reconstructed by subtracting the reference phase from the following 6 flow-sensitive phases $\Phi_i^{(j)}=\Phi v_{j,i} M_{1i}^{(j)}$:

$$v_{j,i} = \frac{\Delta\Phi^{(j)}}{\gamma \Delta M_{1i}^{j}} = \frac{\Phi_i^{(j)} - \Phi^{(ref)}}{\gamma (M_{1i}^{j} - M_{1i}^{ref})}$$

, where i = x,y,z *and* j = *I, II,* and γ = gyromagnetic ratio. The gradient's Maxwell terms were calculated online and corrected during image reconstruction [6]. Based on the low- and high-*venc* velocity data, one set of PC images was created. The high-*venc* scan was used as an estimator for regional velocities to correct for aliasing in the low-*venc* data. The anti-aliasing workflow is shown in Figure 3 using the difference map between the high-*venc* and low-*venc* and thresholds to determine aliased voxels.

The dual-*venc* 2D PC-MRI sequence with 3-directional velocity encoding (TR/TE/FA = 5ms/2.7ms/15˚, temporal resolution = 70ms, $venc_I$/$venc_{II}$ = 100/200 cm/s) was tested with a rotation phantom (Figure 2A) on a 3T MRI scanner (Skyra, Siemens, Germany). In addition, two standard 2D PC-MRI scans were performed for comparison (scan 1: *venc* = 100 cm/s, TR/TE/FA = 5ms/2.7ms/15˚, temporal resolution = 38ms, scan 2: *venc*= 200 cm/s, TR/TE/FA = 4.8ms/2.4ms/15˚, temporal resolution = 40ms). All data were acquired with identical spatial resolution of 1.6x1.6x8mm^3. VNR was calculated using the standard deviation of velocities in successive time frames over the entire rotation phantom and compared between the dual-*venc* and the standard 2D PC-MRI scans.

RESULTS: Dual-*venc* and standard 2D PC-MRI data were successfully acquired (figure 2). The use of a single common reference scan reduced the total acquisition time by 12.5% compared to running two separate scans. The development of the anti-aliasing algorithm using the high-*venc* of the dual-*venc* measurement to find solely the aliased voxels was successfully implemented as shown in figure 2C. An example of the resulting anti-aliased dual-*venc* velocity encoded image of the rotation phantom is shown in the bottom row of figure 3. The dual-*venc* sequence showed an expected improved VNR of 72 in comparison to 35 in the high-*venc* scan and 51 in the low-*venc* scan, which corresponds to a VNR improvement of 206%.

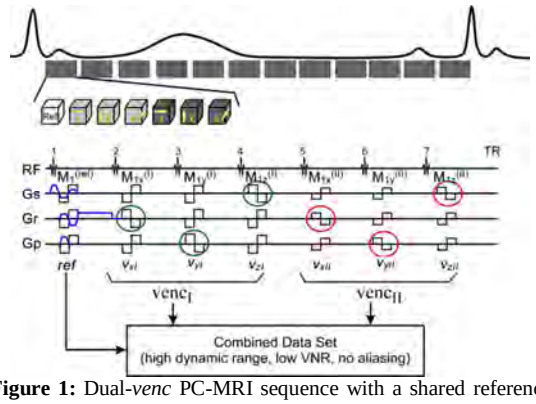

Figure 1: Dual-*venc* PC-MRI sequence with a shared reference scan (ref) followed by low-venc and high-venc velocity encoding in x, y, and z directions. A combined data set for each cardiac time frame was reconstructed utilizing the high VNR low-*venc* scan and high-*venc* data for anti-aliasing.

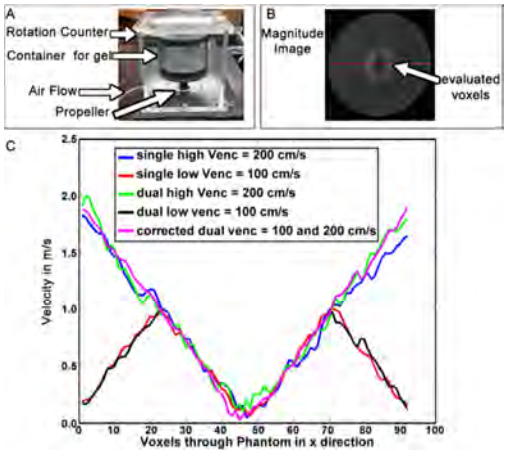

Figure 2: A. Rotation Phantom, B. Magnitude image of an axial cut plane with the analyzed voxels highlighted in red, C. measured velocities of the highlighted voxels. The blue and green curves represent the high-*venc* scans measured with a *venc* of 200 cm/s and the red and black lines represent the low-*venc* scans with aliasing at the outer voxels (*venc* = 100 cm/s). The magenta line represents the combined data set (dual-*venc* corrected scan) showing the result of the anti-aliasing.

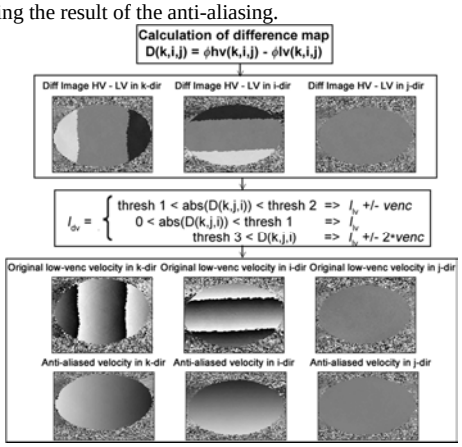

Figure 3: Anti-Aliasing Procedure using the *low-venc* scan as basis image and correcting the aliased voxels by comparing with the high-*venc* scan (working with the difference map and thresholds).

DISCUSSION AND OUTLOOK: In the future, this optimized dual-*venc* PC-MRI sequence can be employed for improved in-vivo blood flow measurement in 4D flow MRI acquisitions or to acquire cardiac motion and intra-cardiac blood flow velocities in a single acquisition. We plan on employing k-t GRAPPA for acceleration to achieve similar scan times as in standard PC-MRI.

REFERENCES: [1] Markl M et al, JMRI 2007; [2] Nett EJ et al JMRI 2012; [3] Johnson K MRM 2010; [4] Nilsson A, JMRI 2012 Dec; [5] Bernstein MA et al, JMRI 1992; [6] Bernstein MA MRM (1998)

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