Free-Breathing Real-Time Flow Imaging using EPI and Shared Velocity Encoding

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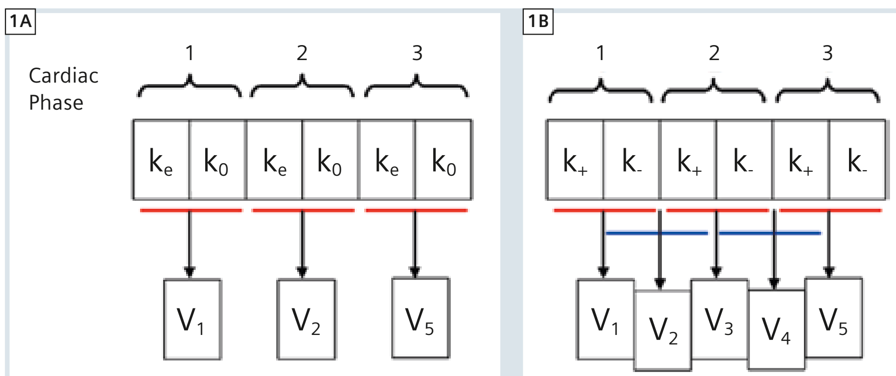
Introduction

Phase-contrast magnetic resonance imaging (PC-MRI) is used routinely as an important diagnostic tool to measure blood flow and peak velocities in major blood vessels and across heart valves. Conventional PC-MRI commonly uses ECG synchronization and segmented *k*-space acquisition strategies [1, 2]; this approach requires breath-holding and regular cardiac rhythm, rendering it impractical in a large number of patients. Alternatively, signal averaging and respiratory gating approaches can be used to reduce respiratory motion artifacts in patients unable to breath-hold, but these methods still require a reliable ECG signal and regular heart beats. Furthermore, the velocity information resulting from an ECG-synchronized segmented PC sequence represents a weighted temporal average of the velocity waveform over the acquisition time; short-lived hemodynamic effects, such as response to pharmacological stress, physical exercise or respiration and interventional maneuvers cannot be assessed. Hence, free-breathing real-time (RT) PC-MRI with sufficient spatial/temporal resolution would be desirable to provide beat-to-beat hemodynamic information to characterize transient blood flow phenomena and as an alternative approach for patients with irregular cardiac rhythm or inability to hold their breath.

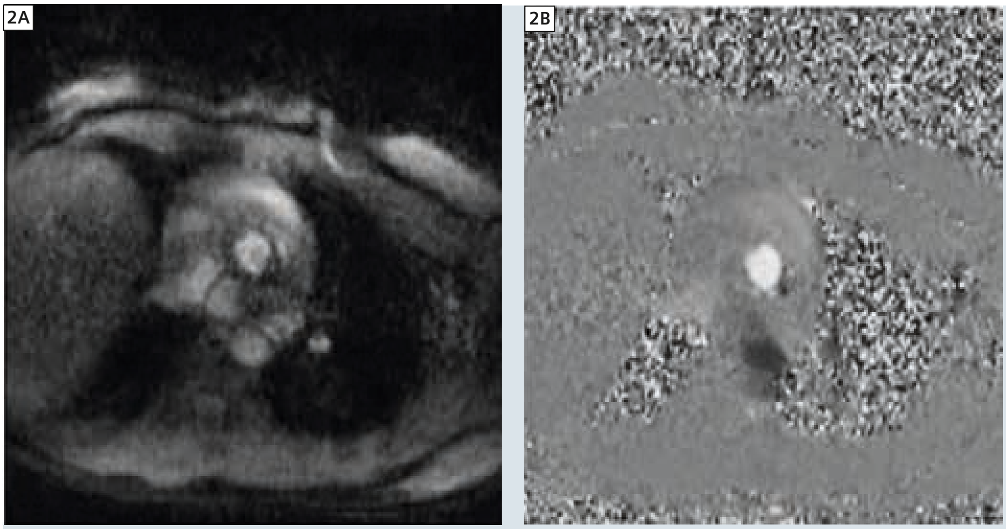


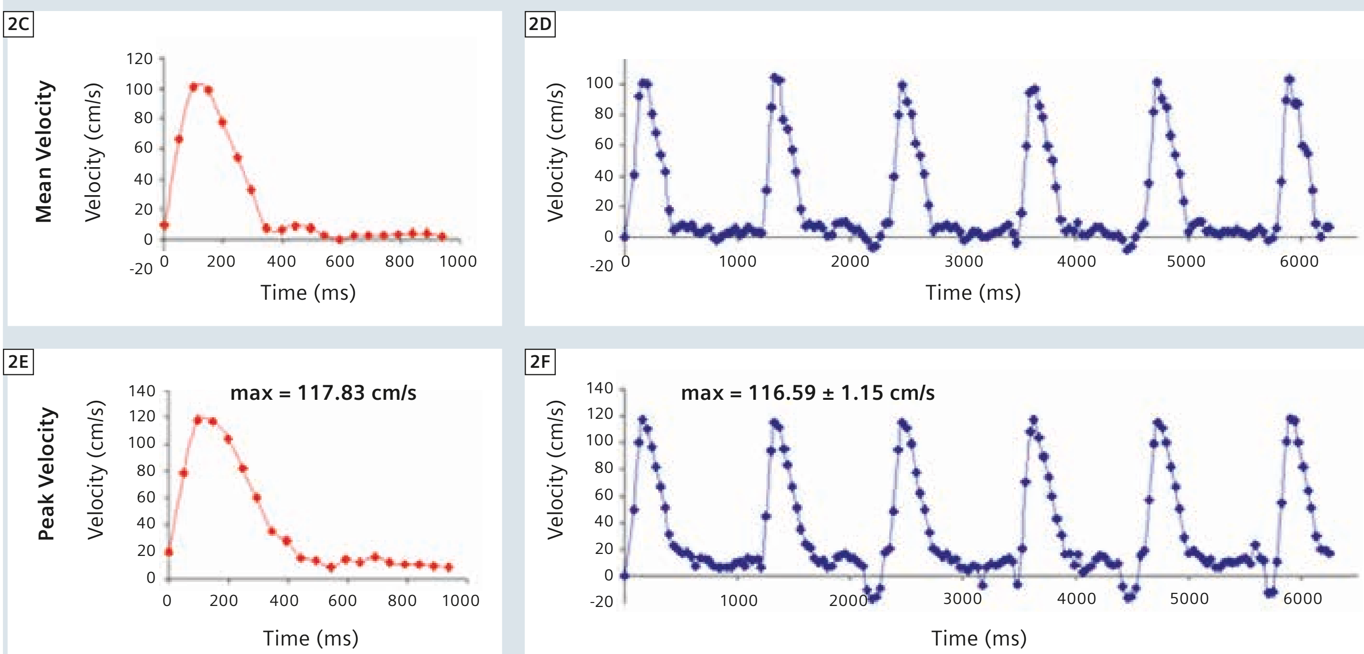
1 **(1A)** The conventional PC with 1-sided velocity encoding. Velocity information was extracted using the flow encoded (k_e) and flow compensated (k_0) data within the same cardiac phase. **(1B)** SVE with 2-sided velocity encoding. Additional velocity frames (V_2 and V_4) are reconstructed by sharing the flow encoded data across cardiac phases to double the effective frame rate by a factor of 2.

Methods

RT PC-MRI sequence was implemented using a gradient-echo echo-planar imaging (GRE-EPI) sampling trajectory with an echo train length (ETL) of 7 to 15 echoes. A rapid phase modulated binomial spatial and spectral selective water excitation pulse was used to eliminate ghosting artifacts from fat tissue. Temporal parallel acquisition technique (TPAT) with an acceleration factor of 3 was used by temporally interleaving undersampled *k*-space lines [3, 4]. Four shots per image were acquired resulting in an acquisition time about 40 to 50 ms (depending on ETL and matrix size) for each full *k*-space dataset per flow encoding step. To further improve the effective temporal resolution of RT-PC, a shared velocity encoding (SVE) [5] scheme was implemented.

In PC-MRI, a critical step is the elimination of background phase errors. This is achieved by subtracting two measurements with different flow encodings. It is typically performed using one of two methods: one-sided velocity encoding in which velocity compensated (k_0) and velocity encoded (k_e) data are acquired for each cardiac phase, or two-sided velocity encoding in which equal and opposite velocity encodings (k_+/k_-) are acquired. Both cases result in a reduc-



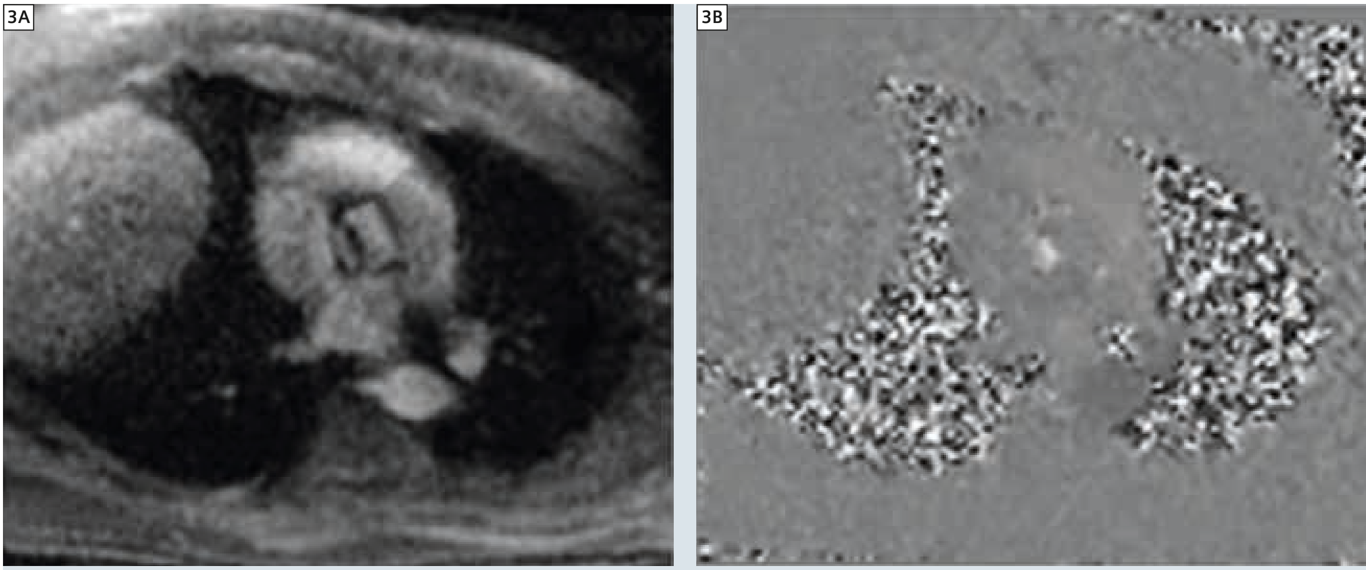


2 Example of magnitude **(2A)** and phase **(2B)** images acquired using RT PC-MRI of the aortic valve in a normal volunteer showing typical image quality. Mean velocity **(2C, 2D)** and peak velocity **(2E, 2F)** waveforms from the same volunteer acquired using ECG-triggered segmented PC-MRI as gold standard and free-breathing RT PC-MRI

tion in temporal resolution or an increase in scan time by a factor of two. The SVE concept is to share flow encoded data between two adjacent frames in a two-sided velocity encoded PC-MRI. Figure 1 illustrates the difference between conventional PC reconstruction with one-sided velocity encoding and SVE reconstruction with two-sided velocity encoding. The odd-number velocity frames (V1, V3 and V5) are identical to the frames generated by the conventional PC reconstruction, while SVE reconstruction results in the intermediate even frames 2 and 4. While each of these additional frames shares velocity data with the adjacent frames, each contains a unique set of data that represents a velocity measurement centered at the time between the original frames. As the result, SVE increases the effective temporal resolution by a factor of two. While the SVE method doubles the effective frame rate; the temporal window of each frame is unchanged. In the RT-PC works-in-progress (WIP) sequence, the effective, reconstructed temporal resolution of each frame is 40 to 50 ms while the temporal window to acquire all flow encoding steps is 80 to 90 ms.

Results

Figure 2 shows the representative magnitude (Fig. 2A) and phase (Fig. 2B) images and the velocity waveforms of the aortic valve in one normal volunteer acquired using ECG-triggered segmented PC-MRI in breath-hold (Figs. 2C and 2E) and RT PC-MRI in free-breathing (Figs. 2D and 2F). The results from ECG-triggered segmented PC-MRI are used as the reference standard. The mean velocity



3 Magnitude **(3A)** and phase **(3B)** images acquired using RT PC-MRI of the aortic valve in one patient with bicuspid aortic valve and moderate aortic stenosis.

curve (Fig. 2D) and the peak velocity curve (Fig. 2F) acquired using RT PC-MRI match well with those of the reference standard (Figs. 2C and 2E). The maximum peak velocity from RT-MRI is 116.59 ± 1.15 cm/s averaged over six heart beats, which agrees well with the reference standard (117.83 cm/s). Figure 3 shows the magnitude and phase images of the aortic valve acquired with RT PC-MRI in one patient with bicuspid aortic valve and moderate aortic stenosis. RT PC-MRI measured a peak velocity of 330 cm/s and planimetered valve area of 1.2 cm^2.

Conclusion

We have described a free-breathing RT PC-MRI technique that employs a GRE-EPI sampling trajectory, TPAT acceleration and SVE velocity encoding scheme. It is a promising approach for rapid and RT flow imaging and measurements. The technique has been shown to provide accurate blood flow measurements with sufficient SNR and spatial/temporal resolution [5]. With RT EPI acquisition, the adverse effects of cardiac and respiratory motion on flow measurements are minimized. Thus, RT PC-MRI can be used on patients suffering from arrhythmia, and in pediatric or other patients incapable of breath-holding. Furthermore, RT PC-MRI provides transient hemodynamic information, which could be used to evaluate the effects of respiration, exercise, or other physical maneuvers on blood flow [6].

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References
1 Chatzimavroudis GP et al. Clinical blood flow quantification with segmented *k*-space magnetic resonance phase velocity mapping. J Magn Reson Imaging 2003;17:65–71.
2 Edelman RR et al. Flow velocity quantification in human coronary arteries with fast, breath-hold MR angiography. J Magn Reson Imaging 1993;3:699–703.
3 Kellman P et al. Adaptive Sensitivity Encoding Incorporating Temporal Filtering (TSENSE). Magn Reson Med. 45: 846-852 (2001).
4 Breuer FA et al. Dynamic autocalibrated parallel imaging using temporal GRAPPA (TGRAPPA). Magn Reson Med. 53(4): 981-985 (2005).
5 Lin HY et al. Shared velocity encoding: a method to improve the temporal resolution of phase-contrast velocity measurements, Magn Reson Med 2012;68:703–710
6 Thavendiranathan et al., Simultaneous right and left heart real-time, free-breathing CMR flow quantification identifies constrictive physiology. JACC Cardiovasc Imaging. 2012 Jan;5(1):15-24.