# 2D PC-MRI with 3D Flow Encoding acquisitions Only (FEsO) for Accurate Slice Orientation-Independent Blood Flow Measurement

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**Introduction:** Phase-contrast MRI (PC-MRI) is a well-established technique for quantification of blood flow. 2D dynamic PC-MRI typically uses the through plane Flow Encoding (FE) for cardiovascular applications. It requires the imaging slice be perpendicular to the blood vessel to ensure measurement accuracy of peak velocity. Quite often, the 2D PC-MRI imaging slices may not be perpendicular to the blood vessel of interest, which could result in significant underestimation of peak velocity. This issue may be mitigated by performing FE not just in the through-plane direction, but also the two in-plane directions[1]. However, such a strategy necessitates a much longer temporal footprint for each cardiac phase than traditional 2D PC-MRI. To address this issue, we assume that, in a relatively short period of time (e.g. duration of two cardiac phases), the blood flow velocity *direction* (not magnitude) does not change significantly. This assumption provides an additional constrain term of velocity direction that can be used to calculate flow compensation (FC) data using three FE data sets only, so that the FC data does not need to be acquired. Hence, we propose to develop a fast 2D dynamic PC-MRI technique with three-directional FE acquisitions Only (FEsO) to calculate the 3D velocity for each pixel, which may resolve the issue of peak velocity underestimation due to non-ideal imaging slice prescription. Prospective *in vivo* studies were performed to evaluate the accuracy of maximum peak velocity and volumetric flow measurements using the proposed FEsO technique.

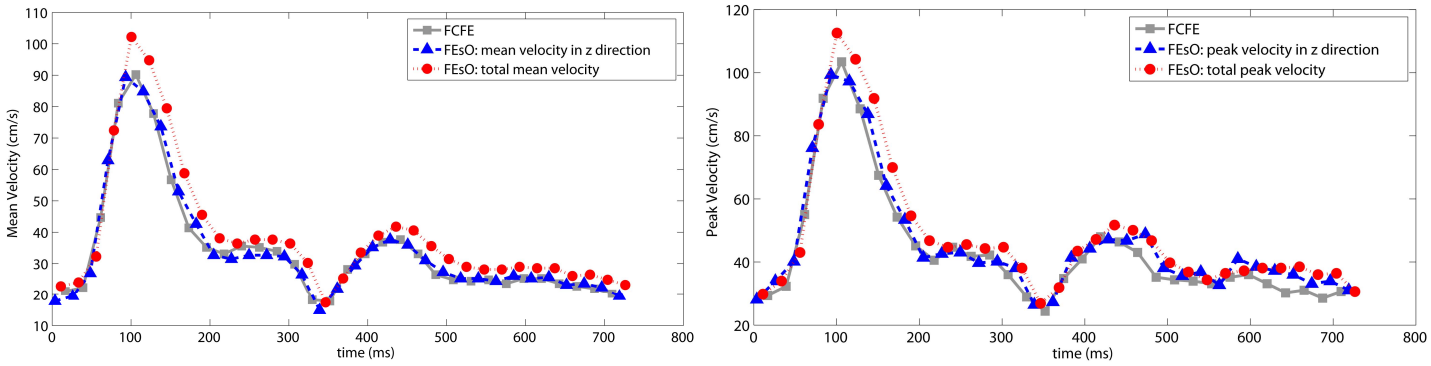
**Methods:** We assume that FC images and velocity directions do not change significantly between two adjacent temporal frames[2]. Velocity of each cardiac phase will be expressed as function of $\phi_0$ (i.e. FC phase): $V_i = \frac{\phi_i - \phi_0}{\pi} * VENC, (i = x, y, z)$. We have the following constrain term for cardiac phase number n and n+1: $min\left|\overrightarrow{V_n} \cdot \overrightarrow{V_{n+1}} - \left|\overrightarrow{V_n}\right| * \left|\overrightarrow{V_{n+1}}\right|\right|$. Minimization of this term ensures that the flow velocities in two adjacent frames, $V_n$ and $V_{n+1}$, are along the same or similar direction as much as possible. The $\phi_0$ was calculated to make the constrain term to achieve its minimal value. Median filter were applied on any pixels whose $\phi_0$ falls outside two standard deviations within its adjacent 3-by-3 pixels or pixels through systolic period. Subsequently, 3D velocities of each cardiac phase were calculated accordingly. In our approach, the FC data is not required for calculation of each directional velocity. Three FE data sets from one cardiac phase before and after the current frame were included for each temporal frame FC data calculation to improve calculation accuracy. The constrain term is ill-conditioned if the magnitudes of $V_n$ and $V_{n+1}$ are similar to each other, which is likely to happen in diastolic frames. To avoid this issue, the mean of the beginning and ending systolic FC images were used as FC for all diastolic frames[2].

Two volunteers (N=2) were recruited for a prospective *in vivo* study and scanned on 1.5T scanner (Siemens, Avanto, Erlangen, Germany) with two-channel neck coils, using both standard FCFE PC-MRI sequence and the proposed FEsO sequence. Both sequences were implemented with VENC=120 cm/s-130 cm/s, 30° flip angle, 501 Hz/Pixel readout bandwidth, TE=5.06 ms, Temporal Resolution=22.35 ms, 208x256 acquired matrix, 162x200 mm$^2$ FOV, and 5 mm slice thickness. Two data sets were acquired in each volunteer: 1) through-plane FCFE with 1 line per k-space segment; 2) FEsO with 1 line per k-space segment. Imaging plane of each data set was at approximately 60° (instead of 90°) angle to the longitudinal axis of the right Common Carotids Artery (rCCA). ROI for the rCCA was drawn for each volunteer to measure the peak velocity waveforms and total volumetric blood flow (we use through plane FE direction of FEsO to calculate flow). All scans were acquired during free breathing with retrospective ECG gating.

**Results:** An example of a healthy volunteer's mean velocity and peak velocity waveforms are shown in Fig. 1. The mean and peak velocity waveforms of traditional through-plane FCFE were similar to the waveform generated based on the z-direction (i.e. through-plane FE direction) velocity of the FEsO data, which had 3D FE directions. However, both provided smaller maximum peak velocity compared to the waveform based on the 3D velocity ($\sqrt{V_x^2 + V_y^2 + V_z^2}$) calculated from the FEsO data (103 cm/s vs 113 cm/s for volunteer1's maximum peak velocities and 97 cm/s vs 115 cm/s for volunteer2's maximum peak velocities). This underestimation of peak velocity was due to the fact that the imaging slice was not perpendicular to the carotid artery. The total volumetric flow measurements were similar for both techniques: 3.64 mL (FCFE) vs 3.69 mL (FEsO) for volunteer1 and 3.97 mL (FCFE) vs 4.18 mL (FEsO) for volunteer2.

**Conclusion:** FEsO can improve blood flow velocity measurement accuracy of 2D PC-MRI compared with through-plane FCFE technique with same temporal resolution for cases where the imaging plane is not perpendicular to the blood vessel of interest.

**References:** 1. Thompson RB., et. al. MRM 2002, 47:499-512 2. Wang D., et. al. MRM DOI: 10.1002/mrm.25133




**(a)** **(b)**

**Fig. 1.** Mean velocity waveforms (a) and peak velocity waveforms (b) from the FCFE PC-MRI (gray curve), FEsO through-plane FE direction (blue curve), FEsO total velocity ($= \sqrt{V_x^2 + V_y^2 + V_z^2}$, red curve). The through-plane direction FEsO results is highly correlated with the measurements from FCFE PC-MRI at the same temporal resolution. The FCFE PC-MRI underestimates the maximum peak velocity due to the fact that the imaging slice is not perpendicular to the blood vessel.