

Rapid Cardiovascular Flow Quantitation Using Slice-Selective Spiral Fourier Velocity Encoding

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Introduction: Accurate flow quantitation is important for the evaluation of many cardiovascular conditions including valvular abnormalities, congenital defects, and coronary artery disease. In cardiac MRI, speed is of particular importance because low time resolution may cause underestimation of peak velocities, and acquisition time is typically limited to the duration of a breath-hold. Conventional 2DFT phase contrast (PC) [1] is inadequate because scan time would be prohibitive and because partial voluming is problematic when flow is highly localized and/or turbulent. We propose the use of Fourier Velocity Encoding (FVE) [2] with low spatial resolution spiral readouts to reduce acquisition time. The use of FVE instead of PC makes it possible to resolve the full velocity distribution within each voxel, avoiding problems related to partial voluming. In the heart, because of the large vessel sizes, low spatial resolution is sufficient to separate vessels and we were able to adequately sample k_x, k_y using a single-shot spiral acquisition. Balancing time and velocity resolutions, we were able to acquire time and spatially-resolved velocity distributions in a single 8-second breath-hold. In the neck, where breath-holding is not required, we used 4 spiral interleaves to achieve higher spatial resolution. The sequence was tested on phantoms and normal volunteers, and the results were compared with Doppler ultrasound.

Methods: Experiments were performed on a GE Signa 3T EXCITE HD system, with gradients capable of 40 mT/m amplitude and 150 T/m/s slew rate. The imaging pulse sequence consisted of a slice selective excitation, a bipolar flow encoding gradient, a spiral readout, and a gradient crusher. The excitation achieved 5 mm slice thickness and 15° flip angle, with a 400 μ s RF pulse and 1 ms gradient. Through plane flow encoding was implemented using a large bipolar pulse that was scaled to achieve different k_v encodings. The size of the largest bipolar is determined by the desired velocity resolution. For the readout, uniform density spirals [3] were used. In the heart, we used a single-shot 6.5 ms readout, achieving 6 mm resolution over an 18 cm FOV. In the neck, we used a 4-interleave 7.6 ms readout, achieving 2.5 mm in-plane resolution over a 20 cm FOV.

Each FVE dataset is a stack-of-spirals in k_x, k_y, k_v space (Fig. 1). Acquisitions were prospectively ECG-triggered, and the k_v encodes were segmented across multiple heartbeats. During each RR interval, 1-4 k_v encodes were repeatedly acquired, resulting in many cardiac phases. The true temporal resolution is thus 1-4-TR, but velocity histograms were reconstructed every TR using a sliding window. Using 32 k_v encodes, a single-shot readout and 50 ms time resolution, it is possible to limit scan time to an 8 heartbeat breath-hold. Time resolution can be improved by increasing the acquisition time or reducing the velocity resolution.

During reconstruction, an x, y dataset is obtained for each k_v encode by gridding and inverse Fourier transform, converting the acquired data $S(k_x, k_y, k_v, t)$ to $S(x, y, k_v, t)$. A region of interest (ROI) in the x, y plane is defined and the complex values of the pixels in the ROI are averaged, and the data set becomes $S(k_v, t)$. Finally, inverse Fourier transform is used to obtain $S(v, t)$, the time-velocity histogram. Initial tests were performed on two flow-phantoms designed by PBD Inc., and then in normal volunteers, aiming at quantifying flow through the common carotid artery and the aortic valve. Doppler ultrasound was used as a “gold standard” in all experiments.

Results and Discussion: The MRI measured time-velocity histograms show excellent agreement with Doppler ultrasound. The peak velocity and the shape of the time-velocity curve from phantoms and normal subjects were comparable to those acquired with ultrasound (Fig. 2). Furthermore, spiral FVE may provide a more precise measurement of the peak velocity, as the ultrasound measurements are often distorted by spectral dispersion and possible errors from angle correction. Qualitatively best results were achieved when using 32 k_v encodes and ± 200 cm/s velocity FOV, or 16 k_v encodes and ± 100 cm/s velocity FOV.

Time-resolution was improved by increasing the number of R-R intervals when imaging the carotid artery. That is also possible in the heart, if the subject is capable of an extended breath-hold, or if the velocity resolution or FOV is reduced. Nevertheless, 8 heartbeat measurements show results comparable to ultrasound even when using 32 k_v encoding steps and 50 ms time resolution. The most noticeable artifacts were ghosting along the velocity axis, due to k_v segmentation.

We expect this technique to accurately measure flow distributions in stenotic jets, as FVE can detect multiple velocities within voxels. Tests in a patient population are planned. The proposed method may be useful for accurate quantitation of abnormal valvular flow, congenital flow defects and coronary flow reserve.

References: [1] Pelc NJ, et al. MRQ 7:229, 1991 [2] Tsai CM, et al. MRM 42:682, 1999 [3] Hargreaves BA, <http://www-mrsrl.stanford.edu/~brian/vdspiral>

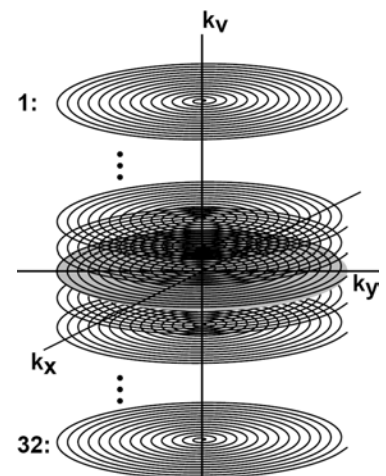


Fig. 1: The dataset corresponding to each temporal frame is a stack-of-spirals in k_x, k_y, k_v space. Each spiral acquisition corresponds to a different k_v encode.

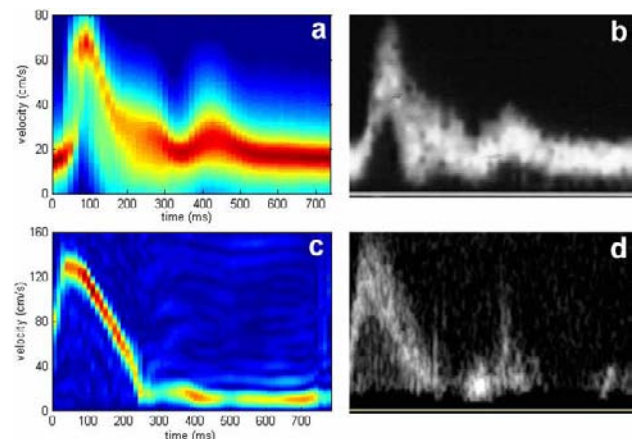


Fig. 2: Time-velocity flow histograms for the common carotid artery, (a) Spiral FVE, (b) Doppler ultrasound, and for the aortic valve, (c) Spiral FVE, (d) Doppler ultrasound.