Carotid wall shear rate measured with spiral Fourier velocity encoding

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Introduction: Fourier velocity encoding (FVE) has been proposed as a method for non-invasively measuring fluid shear rate [1] and hence vascular wall shear stress, an important factor implicated in atherogenesis [2]. Although the scan-time of 2DFT FVE is prohibitively long for clinical use, the recently introduced spiral FVE method [3] shows promise as it is substantially faster (10-40 times). In this work, we investigate the feasibility of using spiral FVE for estimating shear rates near the carotid artery walls in clinically practical scan times.

Methods and Results: The following experiments were conducted: (1) validation of spiral FVE against high-resolution 2DFT phase contrast, using a pulsatile carotid flow phantom; (2) evaluation of resolution requirements, using a numerical phantom; and (3) *in vivo* demonstration. Studies (1) and (3) were performed on a GE Signa 3T EXCITE HD system (40 mT/m, 150 T/m/s gradients). The simulations in (2) were performed in Matlab.

1) Validation against phase contrast: A pulsatile carotid flow phantom (Phantoms by Design, Inc.) was used in this experiment. A slice perpendicular to the carotid bifurcation was prescribed, and through-plane velocities were measured. A gradient-echo 2DFT phase contrast (PC) sequence (0.33 mm resolution, 10 NEX) was used as a gold standard reference. Spiral FVE data with 3 mm resolution was obtained from the same scan plane. Acquisitions were prospectively gated, and we used the same TR, flip angle, slice profile and pre-scan settings for both acquisitions. The total scan time was 40 minutes for PC, and 12 seconds for FVE. A simulated "FVE" dataset $s(x,y,v)$ was derived from the PC data using the following model:

$$s(x,y,v) = \left(m(x,y)\cdot \mathrm{sinc}\frac{v - v_{PC}(x,y)}{v_{res}} \right) * \mathrm{jinc}\frac{\sqrt{x^2+y^2}}{xy_{res}},$$

where $m(x,y)$ and $v_{PC}(x,y)$ are the magnitude and velocity images, v_{res} is the FVE velocity resolution, and xy_{res} is the FVE spatial resolution. The k-space coverage in spiral FVE consists of a stack-of-spirals in $k_x\, k_y\, k_v$ [3]. Therefore, **sinc(*v*)** and **jinc(*r*)** are the blurring kernels associated with the rectangular and circular coverages in k_v and k_x-k_y, respectively. Registration between PC-derived and measured FVE data was done using the phase difference in k-space to estimate the spatial shift. Amplitude scaling was done by normalizing the total energy in each set. The results for two representative pixels are shown in Fig. 1. PC-derived (left) and measured (center) FVE histograms are in good agreement. The difference between histograms (right) has 10dB less energy.

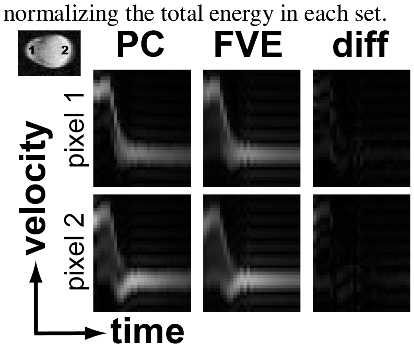

Fig. 1: Spiral FVE validation against high-resolution 2DFT phase contrast, using a pulsatile carotid flow phantom. The PC-derived FVE histogram (left) agrees very well with the measured spiral FVE data (center). Pixels 1 and 2 were selected near opposite vessel walls.

2) Resolution requirements: In order to evaluate the spatial resolution and velocity resolution requirements for shear rate estimation using spiral FVE, a numerical phantom with spatially varying velocities was designed, and used as input to the model described above. The peak velocity was set to 70 cm/s, with shear rate values ranging from 250 to 700 s^{-1} (Fig. 3, left). We then varied v_{res} and xy_{res}, and computed the shear rate (dv/dr) using the method proposed by Frayne et al. in [1]. A region-of-interest (ROI) was defined around the vessel, and for each pixel, the percentage error was calculated.
The mean percentage error within the ROI for each xy_{res}-v_{res} pair is shown in Fig. 2. The best result (15±10%) was obtained using 3 mm spatial resolution. No significant improvement was observed from using velocity resolutions above 10 cm/s. Using this resolution pair, the method is capable of successfully resolving regions of low and high shear rate (Fig. 3).
We also observed that the mean percentage error increases when using higher spatial resolution (Fig. 2). This is because the Frayne method requires the voxel to be large enough to straddle the blood-vessel wall interface [1]. Therefore, the optimal spatial resolution must be dependent on the width of the viscous sublayer (dr), which is spatially-varying. To investigate this hypothesis, the experiment was repeated using three smaller ROIs, with mean shear rate values of 280, 545, and 680 s^{-1}, respectively. The optimal resolutions were found to be 7 mm, 2 mm, and 1.5 mm, respectively.

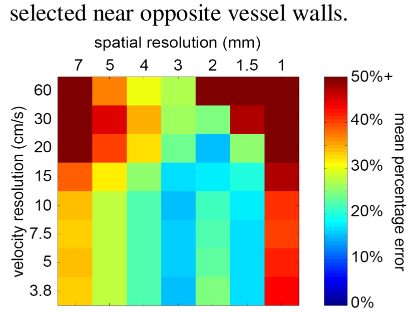

Fig. 2: Shear rate mean percentage error within the ROI for different spiral FVE resolutions (numerical phantom).

3) *In vivo* demonstration: A healthy volunteer's left carotid artery was imaged using multi-slice spiral FVE with 1.4 mm spatial resolution, 15 cm/s velocity resolution, and 24 ms temporal resolution. The total scan time was 32 heartbeats per slice. Measured shear rates are shown in Fig. 4. Note that the method accurately detects the wall corresponding to the external carotid artery as having lower shear rate.

Discussion: Velocity histograms obtained with spiral FVE showed good quantitative agreement with those obtained using high-resolution PC. We have shown that spiral FVE can potentially be used with the method by Frayne et al. for estimating carotid wall shear rate (dv/dr), in clinically practical scan time (32 heartbeats per slice). We also presented a study of resolution requirements, where we concluded that velocity resolutions on the order of 10-15 cm/s are sufficient. With respect to the optimal resolution, we believe this to be dependent on the width of the viscous sublayer (dr), which is unknown and spatially-varying. Therefore, a reasonable approach would be to use high spatial resolution (~1.5 mm), and then retrospectively blur regions where measured velocity distributions do not contain the entire range of velocities (dv). An evaluation of the method's performance in the presence off-resonance is planned.

Ref: [1] Frayne R, et al.MRM 34:378, 1995. [2] Thubrikar MJ, et al. Ann Thorac Surg 59:1594, 1995. [3] Carvalho JLA, et al. MRM 57:639, 2007.

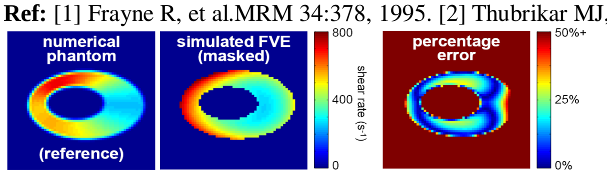

Fig. 3: Shear rate simulation results. The spiral FVE estimate (center) is able to successfully resolve regions of low and high shear rate in the numerical phantom (left).

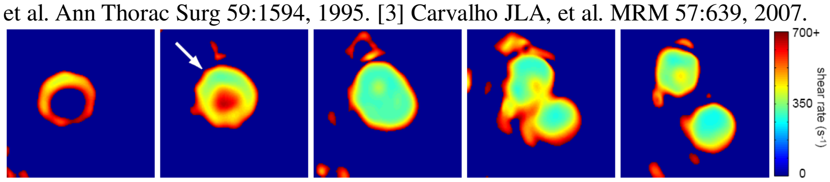

Fig. 4: *In vivo* carotid shear rate measurements using spiral FVE. Lower shear rate was measured near the wall corresponding to the external carotid artery (arrow).