In vivo assessment of carotid wall shear rate using spiral Fourier velocity encoding

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Introduction: Arterial wall shear stress is widely believed to influence the formation and growth of atherosclerotic plaque [1-3], however, there is currently no gold standard for its *in vivo* measurement. High-resolution phase contrast is impractical due to partial-volume effects, long scan times, and inadequate SNR. In 1995, Frayne and Rutt [4] proposed a novel method for non-invasively estimating wall shear rate (WSR) using 2DFT Fourier velocity encoding (FVE). In this work, we evaluate the use of spiral FVE [5] as a rapid method for assessing WSR in the carotid arteries.

The Frayne method: The intra-voxel velocity profile $v(r)$ is estimated with submillimeter resolution from the voxel's velocity distribution $s(v)$, measured with FVE [4]. Assuming that $v(r)\approx 0$ at the vessel wall, and that $v(r)$ is monotonically increasing, $v(r)$ is calculated by inverting the discrete function $r(v_i)$, which is constructed as follows: $r(v_i) = r(v_{i-1}) + \Delta r\,|s(v_i)| \,/\, \sum|s(v)|$, where Δr is the radial extent of the voxel [4]. This process is demonstrated graphically in Fig. 1.

Spiral FVE: The pulse sequence consists of slice-selective excitation, a velocity-encoding bipolar gradient along z, a 4 ms spiral readout along x,y, and a spoiler gradient [5]. The acquired data is stack-of-spirals in k_x,k_y,k_v [5]. For the proposed application, spiral FVE requires approx. 7 times less scan-time than 2DFT FVE.

Numerical validation: The intrinsic accuracy of the proposed method was verified as follows. A velocity map $v(x,y)$ was obtained through computational fluid dynamics (CFD) simulation of carotid flow [6] (Fig. 2a). The true WSR map (WSR_{CFD}) was estimated from $v(x,y)$ through 2D weighted least-squares polynomial fit (Fig. 2b). Simulated spiral FVE data $s(x,y,v)$ was obtained by convolving $v(x,y)$ with $\mathrm{jinc}(\sqrt{x^2+y^2}/\Delta r)$ and $\mathrm{sinc}(v/\Delta v)$, which are blurring functions that model spiral FVE's k-space truncation (circular in k_x,k_y, rectangular in k_v) [7]. The spatial-velocity resolution was set to Δr = 1 mm and Δv = 12.5 cm/s. Then, the Frayne method was used to estimate WSR from $s(x,y,v)$ (Fig. 2c). The results (WSR_{FVE}) were quantitatively compared to the true WSR values, by calculating the percent error as: $100\% \times (WSR_{FVE} - WSR_{CFD}) \,/\, WSR_{CFD}$ (Fig. 2d). The proposed method was able to estimate WSR with ≤10% error for 50% of the voxels, ≤20% error for 80% of the voxels, and ≤30% error for 95% of the voxels (Fig. 2e).

***In vivo* demonstration:** CINE spiral FVE scans were performed on 3 healthy subjects, on a GE Signa 3T EXCITE HD system (40 mT/m, 150 T/m/s). Scan parameters: 1.4 x 1.4 x 5 mm^3 spatial res., 5 cm/s velocity res., 24 ms temporal res., 2-minute acquisition (per slice). For each volunteer, 5 contiguous slices were prescribed perpendicular to the left carotid bifurcation. Slices were imaged independently, in separate scans. WSR estimates were obtained using the Frayne method. Signal variations due to in-flow enhancement and tissue properties were addressed as proposed in [4]. A representative set of results is shown in Figure 3.

Conclusions: We have demonstrated a method for non-invasive *in vivo* assessment of carotid wall shear rate. Spiral FVE [5] acquisitions were used with the reconstruction method proposed by Frayne and Rutt [4]. The intrinsic accuracy of the proposed method was verified using data from CFD simulation. The same approach could be used to evaluate the method's sensibility to factors such as off-resonance, in-flow enhancement, and blood/vessel wall signal differences. Spiral FVE is uniquely suitable for *in vivo* WSR estimation, as it is the only currently available FVE method capable of providing fully resolved spatial localization in clinically practical scan time. The proposed method may facilitate our understanding of the relationship between hemodynamics and plaque growth.

Acknowledgment: The authors thank Lisong Ai and Tzung Hsiai for providing the CFD velocity map used in this work.

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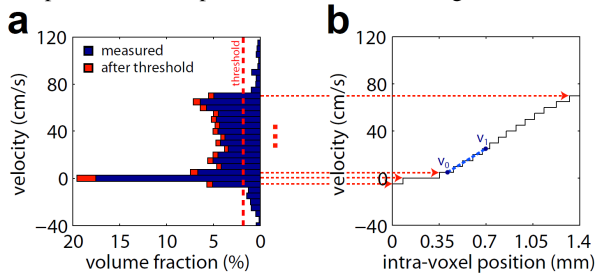

Fig.1: Graphical illustration of the Frayne method [4]. WSR is estimated from FVE velocity distributions in voxels spanning the blood/vessel wall interface. First, a threshold is applied to the velocity histogram to reduce noise sensitivity (a). Then, the volume fraction within each velocity bin is converted into a radial position across the voxel. Finally, the velocity gradient is estimated from the reconstructed velocity profile (b), through linear regression within a small velocity interval (v_0,v_1).

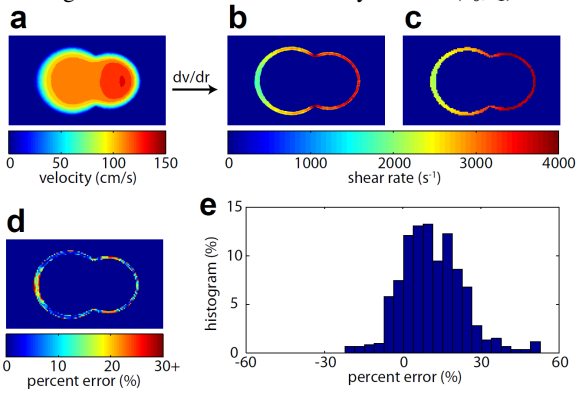

Fig. 2: Numerical validation of the proposed method: (a) CFD velocity map; (b) true WSR map; (c) WSR map measured from simulated spiral FVE data; (d) error map; (e) error histogram.

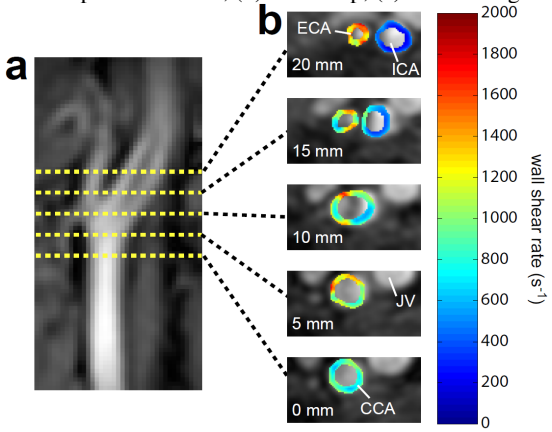

Fig. 3: *In vivo* demonstration of the proposed method. WSR was estimated at the carotid bifurcation of a healthy volunteer. Values are shown for manually-segmented regions-of-interest, at peak flow. (a) slice prescription; (b) FVE-measured WSR values. Scan-time was 128 heartbeats (≈2 minutes) per slice.