Carotid wall shear rate measured with spiral Fourier velocity encoding

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Introduction: Arterial wall shear stress (WSS) -- the drag force acting on the endothelium as a result of blood flow -- is widely believed to be a predictor of locations of formation and growth of atherosclerotic plaque [1-3]. WSS can be estimated as the product of wall shear rate (WSR) and blood viscosity, where WSR is the radial gradient of blood flow velocity (dv/dr) at the wall. Phase contrast MRI is inadequate for assessing WSR, due to partial volume [4] and signal-to-noise ratio (SNR) issues and tradeoffs (Fig.1). We propose the use of spiral Fourier velocity encoding (spiral FVE) [5] for estimating carotid fluid shear rate (FSR). Simulations, as well as in vitro and in vivo experiments are presented.

The Frayne method: We used the method proposed by Frayne et al. for estimating fluid shear rates using FVE [6]. This consists in obtaining the velocity distribution for a voxel at the vessel wall, and then using the distribution to reconstruct the velocity profile across the voxel. The distributions are converted into velocity profiles with sub-voxel spatial resolution, and the reconstructed profiles are then used to obtain shear rate estimates. In a pre-processing stage, a threshold is applied to address rectified noise, and the velocity distribution is compensated for signal differences between blood and vessel wall, as well as saturation effects (Fig.2).

Spiral FVE vs. 2DFT phase contrast: We used a pulsatile carotid flow phantom in order to compare velocity distributions measured with spiral FVE to those derived from velocity and magnitude maps measured with 2DFT phase contrast (0.33 x 0.33 x 3 mm resolution). The phase contrast (PC) maps were blurred using the appropriate convolution kernels -- a jinc along the spatial dimensions, and a sinc along the velocity dimension -- in order to match the spatial and velocity resolutions of the spiral FVE acquisition (3 mm, 10 cm/s).

Fig.3 shows measured and PC-derived time-velocity FVE distributions from two representative voxels, selected near opposite walls of the vessel's bifurcation, as indicated. The signal-to-error ratio between measured and PC-derived time-velocity distributions was in the range of 10-12 dB within the lumen. The data show good visual agreement.

Feasibility of the spiral FVE/Frayne method: A simulation was used in order to evaluate the feasibility of using spiral FVE, combined with the Frayne method, for estimating carotid FSR. We obtained simulated spiral FVE distributions by appropriately blurring (jinc/sinc) a velocity map obtained from a carotid flow simulation using computational fluid dynamics (CFD). The shear rates were then estimated using the Frayne method, and compared to the true values.

The results are shown on Fig.4. Within a region-of-interest defined near the wall-blood interface, the spiral FVE/Frayne method was able to estimate the shear rate with at least 10% accuracy for 50% of the voxels, at least 20% accuracy for 80% of the voxels, and at least 30% accuracy for 95% of the voxels.

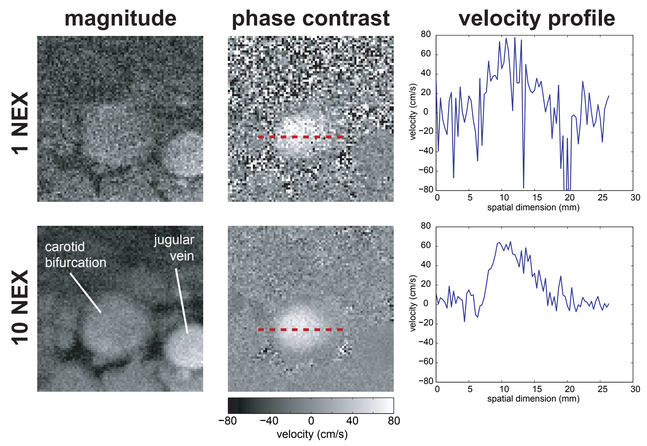

Figure 1: It is not possible to achieve sufficient SNR in clinically practical scan time when estimating shear rates with phase contrast. Scan parameters: 0.33x0.33x3 mm resolution, 2 minutes per NEX.

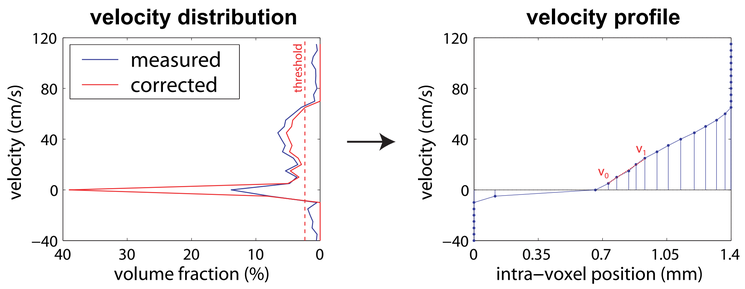

Figure 2: Construction of the intra-voxel velocity profile from the FVE measured velocity distribution, using the Frayne method. After pre-processing, the volume fraction at each velocity bin is converted into a position within the voxel, and dv/dr is calculated.

In vivo demonstration: Healthy subjects were imaged at 3T. The results show the variation in FSR along all three spatial dimensions near the carotid bifurcation, and also the oscillatory pattern of carotid FSR along the cardiac cycle (Fig.5). These are the first in vivo results obtained using the Frayne method, which was originally only demonstrated in vitro. Acquisition time was 2 minutes per slice, spatial resolution was 1.4 mm, and temporal resolution was 24 ms.

Conclusions: We have demonstrated a technique for non-invasive assessment of carotid fluid shear rate, using spiral FVE. The first in vivo results using the Frayne method were presented. The results show the variation in carotid FSR along all three spatial dimensions, and also along the cardiac cycle. The achieved temporal resolution was sufficient to capture the oscillatory pattern of carotid FSR, an important indicator of atherosclerotic plaque growth and risk of rupture. The proposed spiral FVE/Frayne method can potentially help answering questions about the causes of plaque growth and rupture, and could eventually be clinically useful as part of a screening test for predicting carotid atherosclerosis.

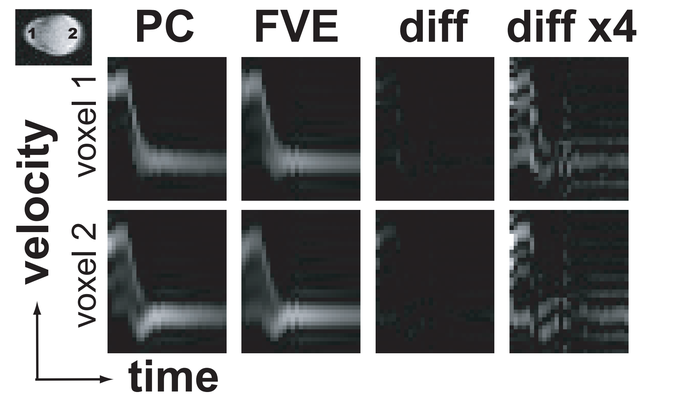

Figure 3: In vitro comparison between time-velocity distributions derived from 2DFT phase contrast and those measured with spiral FVE.

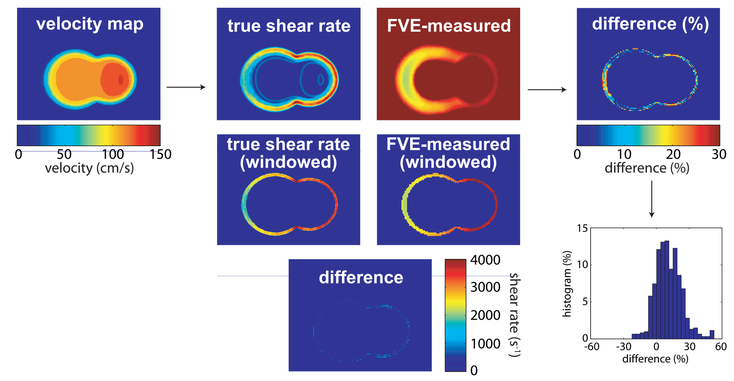

Figure 4: Shear rates measured using the spiral FVE/Frayne method on simulated velocity distributions obtained from a CFD simulation.

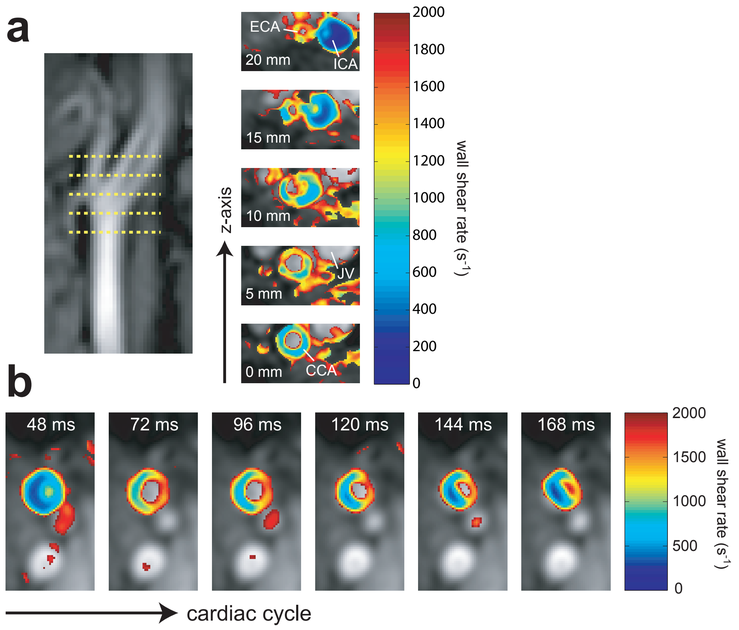

Figure 5: In vivo results: (a) spatial variation in FSR along all 3 dimensions, near the carotid bifurcation; (b) oscillatory pattern along the cardiac cycle (CCA).

References:

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