In-Vitro Validation of Phase Contrast MRI in a Stenotic Phantom Under Steady Flow Using PIV

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Introduction: Blood flow dynamics has an important role in atherosclerosis initiation, progression, and thrombosis leading to occlusive arterial diseases [1]. Since the development of Phase Contrast MRI (PC-MRI), it has been widely used to measure the velocity and flow in blood vessels. Accuracy of the PC-MRI velocity measurements in a 1.5T scanner has previously been evaluated using Laser Doppler Anemometry (LDA) as the gold standard [2]. In this study, we used PC-MRI on a 7T scanner to estimate the velocity field in a severely stenosed phantom and compared the results with those obtained by Particle Image Velocimetry (PIV) technique. Unlike LDA, PIV provides a snapshot of the entire velocity field and consequently serves as more appropriate basis for validation purposes.

Flow model: An idealized rigid axisymmetric Gaussian shape at 90% area occlusion with a 2.54 *cm* upstream diameter was used as a phantom model of peripheral arterial stenosis. A solution of glycerol and water (60:40, w/w) was prepared and then Sodium Iodide was added in order to match its refractive index to that of the phantom for the purpose of optical measurements. The final density and viscosity of the solution was 1600 *kg/m3* and 0.02 *Pa.s*, respectively at 65℉ (T1 = 383 *ms*, T2 = 33 *ms*). Steady inlet flow of 37.1 *ml/s* was employed to produce Reynolds number of 152. These parameters mimic the flow of the human common iliac artery. Three diameters proximal and 13 diameters distal to the stenosis throat were studied.

PC-MRI: Sagittal images along the long axis of the phantom were acquired using a 7T Bruker MR scanner (Bruker Medical GMBH). The imaging parameters were as follows: slice thickness = 2.0 mm, pixel size = 0.18 mm, TE = 6 ms, TR = 20 ms, number of signal averages = 2, and Field of View (FOV) = 69.12 mm × 46.00 mm. Since the FOV was not long enough to cover the entire phantom length, multiple overlapping zones were imaged and merged together. Velocity encoding (Venc) was varied for each imaging zone according to the maximum velocity obtained in PIV. Venc ranged between 20-100 cm/s and 3-20 cm/s for the axial (read-out) and radial (phase-encoding) directions, respectively.

PIV: A 532-nm laser light sheet was passed through the sagittal plane of the phantom, parallel to the flow direction in order to illuminate the flowing fluorescent particles. A set of image pairs were captured and the fluid velocity was extracted using a cross-correlation scheme. The field of view of each camera was about 34.2 *mm* × 34.2 *mm* yielding a nominal spatial resolution of about 0.4 *mm* for the velocity data points.

CFD: Velocity distributions over the phantom volume were calculated after solving the velocity field using the conservation of mass and momentum equations for an incompressible fluid flow, using the CFD software package FLUENT 6.0 based on a finite volume scheme.

Results: In this study, we compared the velocity field obtained by MRI with high resolution PIV results. Fig. 1 is a representative snapshot of a single FOV from PC-MRI data. Note the reverse flow in the recirculation zone just downstream of the stenosis.
As depicted in Fig. 2, our results revealed good agreement between these modalities in the region before and after the stenosis throat. However, several diameters distal to the stenosis, the data became erroneous. We believe that this phenomenon is not a flow dependent error rather it stems from merging sagittal slices. Later, as the flow recovers, the error decreases again. Errors in velocity can be attributed to several sources including low signal to noise ratio, additional phase shifts due to non-constant velocities, and non-stationary transit-time effects. Furthermore, when imaging larger FOVs, hardware issues such as gradient field linearity and B1 field homogeneity play an important role in the accuracy of the velocity data.

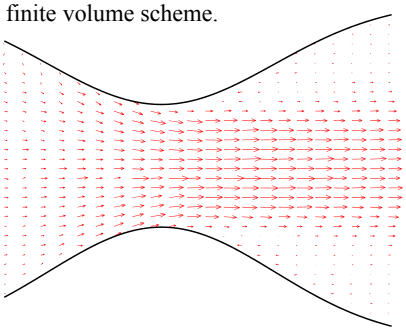

Fig. 1: MR-based peri-stenotic vector field.

References: [1] Nesbitt WS et al. Nat Med. 2009;15:665-73. [2] Siegel JM et al. J Biomech. 1996; 29:1665-72.

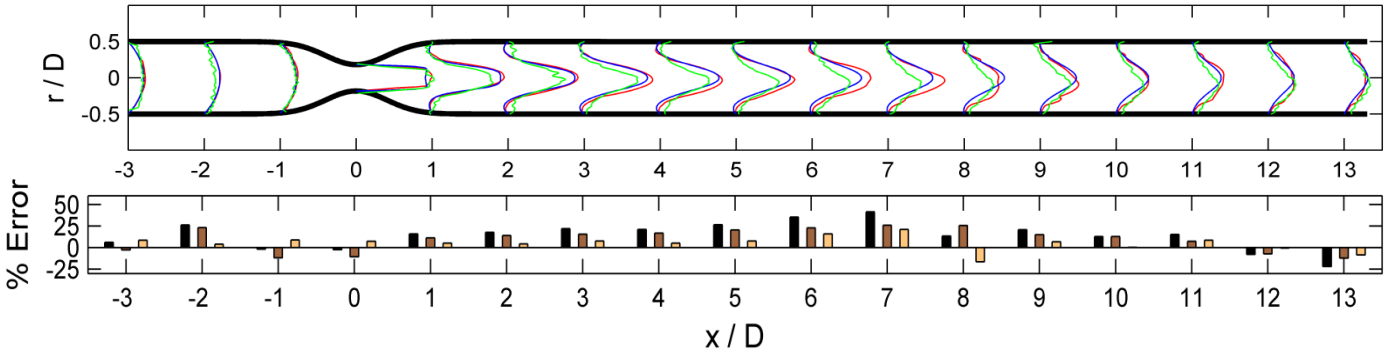

Fig. 2: (Top) Axial velocity profiles for MRI (green), PIV (red), and CFD (blue). All velocities are normalized to the maximum axial velocity obtained by PIV. (Bottom) Percent error of the maximum axial velocity at various cross-sections among different modalities (Black: MRI relative to PIV; Brown: MRI relative to CFD; Yellow: CFD relative to PIV). D specifies the phantom diameter upstream of the stenosis (25.4 *mm*).