Simulation of Phase-Contrast MRI Intravoxel Velocity Standard Deviation (IVSD) Mapping

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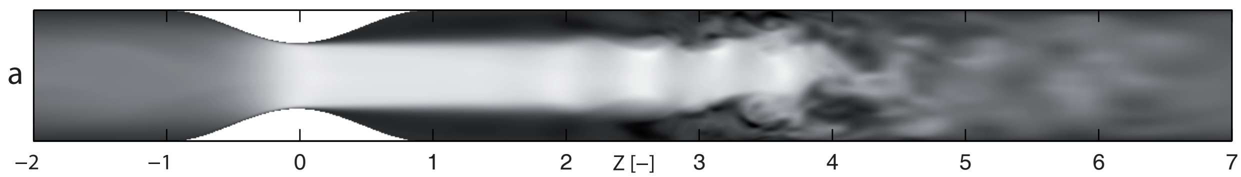
Introduction: Disturbed blood flow, characterized by velocity fluctuations, accompanies many cardiovascular diseases and may contribute to their progression [1]. Phase-contrast (PC) MRI intravoxel velocity standard deviation (IVSD, σ) mapping permits the quantification of the intensity of velocity fluctuations (turbulence intensity) [2]. This is achieved by exploiting how the presence of multiple spin velocities within a voxel affects the MR signal magnitude under the influence of a bipolar gradient. To further develop PC-MRI IVSD mapping, tools for optimization, quality control and validation are needed. We have previously presented an Eulerian-Lagrangian approach for the simulation of PC-MRI velocity measurements of turbulent flow [3]. This approach is here utilized for the simulation of PC-MRI IVSD mapping of turbulent stenotic flow. For validation, the simulation is compared with an in-vitro IVSD measurement.

Methods: PC-MRI IVSD mapping was simulated by solving the Bloch equations using an Eulerian-Lagrangian approach, in which the particle trajectories of virtual spin packets are computed from time-resolved CFD data resolving the velocity fluctuations. Data describing the gradients and RF-pulses in a 3D PC-MRI pulse sequence were exported from the scanner software (Philips Achieva). The IVSD was calculated as σ = sqrt[2ln(|S(0)|/|S(k_v)|)]/ k_v^2, where $k_v=\pi/VENC$, describes the applied motion sensitivity, $S(0)$ is the MRI signal from a scan with k_v=0 and $S(k_v)$ is the signal from a motion encoded scan [2].

The CFD data were obtained from large eddy simulations [4] on a fix structured mesh with a temporal resolution of 50 µs. The geometry comprised a straight rigid pipe with an unconstricted diameter of 14.6 mm and a cosine-shaped stenosis with an area reduction of 75% (Figure 1a). The simulated flow had a Reynolds number of 1000 in the unconstricted part of the pipe.

For validation, the simulated IVSD measurements were compared with an in-vitro PC-MRI measurement made on a phantom with the same geometry and flow settings as used in the simulation. The VENC was 1.5 m/s, the voxel size was 2x2x2 mm^3 and slice-encoding was in the principal flow direction. For further comparison, the root-mean-square (RMS) of the fluctuating velocity was computed from the CFD data.

Results: The IVSD obtained from the PC-MRI simulation show good agreement with both the measurement data and the CFD data (see Figure 1 b-d). The jet in the in-vitro flow seems to be slightly longer than the jet in the CFD data (Figure 1b).



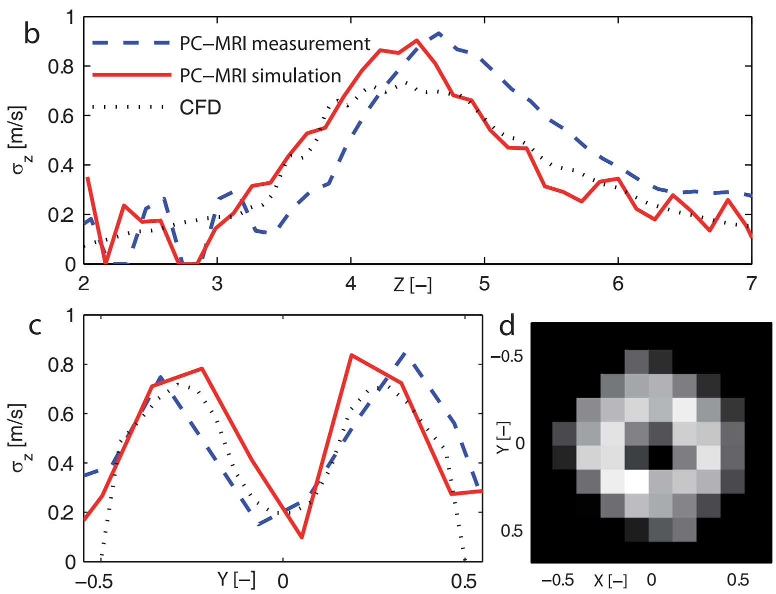


Figure 1. a) The velocity in the principal flow direction (Z) from one timeframe of CFD data (white represents 4 m/s and black -1 m/s). b) The CFD RMS values and the measured and simulated IVSD, σ_z, in the principal flow direction, along the centerline of the phantom and c) along the radius at the reattachment zone. d) Simulated image of the IVSD, σ_z, in the principal flow direction in a cross-section of the phantom at the reattachment zone, from the PC-MRI simulation (white represents 1 m/s and black 0 m/s). X, Y, Z describe the distance from the center of the stenosis and are normalized by the unconstricted pipe diameter.

Discussion: A PC-MRI IVSD measurement in stationary stenotic flow was simulated. This was done by using time-resolved CFD data that resolves the velocity fluctuations in turbulent flow. The overall strong similarities between the PC-MRI IVSD simulation and the measurement (Figure 1b-c) are encouraging and demonstrate the validity of the method proposed. Especially in the radial plots, the excellent agreement between IVSD and RMS values support previous studies [5, 6], indicating that the effects of intravoxel mean velocity variations on PC-MRI IVSD mapping are negligible. The simulation of 3D PC-MRI of fluctuating flow may assist in improving the understanding of the effects of velocity fluctuations on the PC-MRI signal and for the optimization of IVSD mapping.

References: [1]. Nichols W, et al., *McDonald's Blood Flow in Arteries*, 2005, Hodder Arnold. [2]. Dyverfeldt P, et al., MRM 2006;56(4):850-858. [3]. Petersson S, et al., *Simulation of Phase-Contrast MRI of Turbulent Flow*, 2009, ISMRM Workshop on Cardiovascular Flow, Function and Tissue Mechanics. [4]. Mathieu J, et al., *An Introduction to Turbulent Flow*, 2000, Cambridge University Press. [5]. Dyverfeldt P, et al., MRI 2009;27(7):913-922. [6]. Siegel Jr. J, et al., MRM 1997;37(4):609-614.