Application of full turbulent tensor in estimation of MR-based relative pressure

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Target audience: Researchers and clinicians with interest in clinically quantifiable hemodynamic parameters

Purpose: Estimation of relative pressures has been enabled by recent advances in Magnetic Resonance (MR) velocimetry, which allow 3-component velocity-vector fields to be measured in space and time. However, in turbulent flow significant errors occur if the pressure equations are solved with the assumption of laminar flow and neglecting turbulent components, namely Reynolds normal and shear stresses. Turbulent flow can be present in the vasculature where there is abnormal lumen narrowing and results in energy dissipation and unrecoverable pressure loss. This study investigates the importance of including turbulent terms in calculating pressure in comparison with laminar flow assumption. The current technique of MR-based turbulence quantification [1] is limited to only three Reynolds normal stresses. This study employs one of the recently proposed MR-based methods of quantifying the full turbulence tensor – including three Reynolds shear stresses – to obtain all the six components required to solve the partial pressure equation.

Methods: A condition likely to cause turbulence was considered by numerically simulating the flow in a 75%-stenosed tube with a 14.6 mm diameter with a steady inlet flow condition of Reynolds number 4000. The Navier-Stokes equations were solved (ANSYS CFX 14.5) followed by resolving turbulent flow fluctuations using a Large Eddy Simulation (LES)[2]. Phase-contract MRI (PC-MRI) simulations were derived from the LES data by first re-gridding to 1.5-mm isotropic voxels within which velocity distributions were obtained using a 3D Gaussian point spread function. The PC-MRI signal for each direction was computed as the Fourier transform of the velocity distribution with the value of VENC set to 0.5 m/s. The simulated for six flow-encoding directions based on the ICOSA6 encoding scheme [3], which enables estimation of the six-component turbulence tensor. With laminar and fluctuating flow, pressure gradients of Navier-Stokes equations were first derived employing only mean velocities and then by also including Reynolds stresses (blue-colored terms in the equation) yielding relative mean and relative mean turbulent pressure respectively.

$$\frac{\partial \bar{P}}{\partial x_i} = -\rho\left(\bar{v}_1\frac{\partial \bar{v}_i}{\partial x_1} + \bar{v}_2\frac{\partial \bar{v}_i}{\partial x_2} + \bar{v}_3\frac{\partial \bar{v}_i}{\partial x_3} + \frac{\partial \overline{v_1' v_i'}}{\partial x_1} + \frac{\partial \overline{v_2' v_i'}}{\partial x_2} + \frac{\partial \overline{v_3' v_i'}}{\partial x_3}\right) + \mu\left(\frac{\partial^2 \bar{v}_i}{\partial x_1^2} + \frac{\partial^2 \bar{v}_i}{\partial x_2^2} + \frac{\partial^2 \bar{v}_i}{\partial x_3^2}\right), i = 1,2,3$$

Results: Comparison between the two estimations of relative mean pressure – laminar (non-turbulent) and turbulent – reveals marked differences. Figure 1 shows the computed pressure maps, including the LES-derived pressure as the truth reference. Centerline pressure, which is a clinically relevant metric, is shown in Figure 2, estimated using the entire (a) and only the centerline (b) flow region. Including turbulence effects does not result in significant change in pressure drop when potential partial-volume effects at the boarders are avoided (Figure 2a). Computed from the entire flow region, turbulent pressure estimations show lower pressure recovery, 25%, compared to laminar case (81%) and more consistent with reference value (35%).

Discussion & Conclusion: An MR-based method of estimating relative pressure has strong advantages for the assessment of the hemodynamic significance of a given lesion since it offers non-invasive and repeatable measurements compared to the invasive standard method of catheterization [3]. Conditions where estimation of pressure changes are valuable are regions of constriction that produce a jet of blood flow that can promote turbulence generation, such as aortic coarctation. Our results show the significance of taking into account the turbulent property of the flow in pressure estimation of clinically relevant parameters.

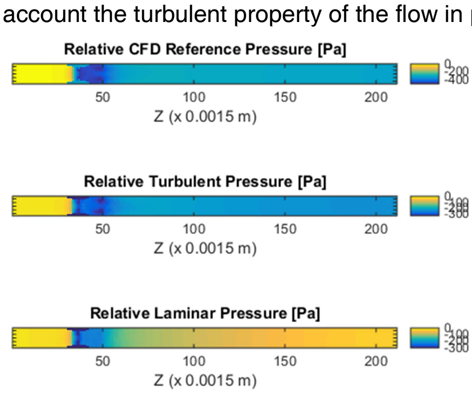

Figure 1: Relative pressure maps in 75%-stenosed tube with stenosis throat at z=37.

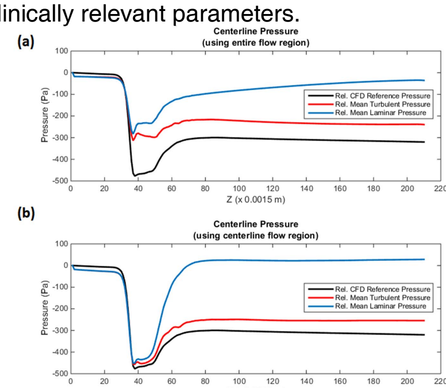

Figure 2: Centerline pressures computed from the entire (a) and centerline (b) flow region of the 75%-stenosed tube.

References: [1] Dyverfeldt et al., Magn Reson Med (2006), [2] Zwart and Pipe, Magn Reson Med (2013), [3] Ebbers and Farnebäck, Magn Reson Med (2009).