The effect of resolution on viscous dissipation measured with 4D-flow MRI in patients with Fontan circulation: Evaluation using computational fluid dynamics

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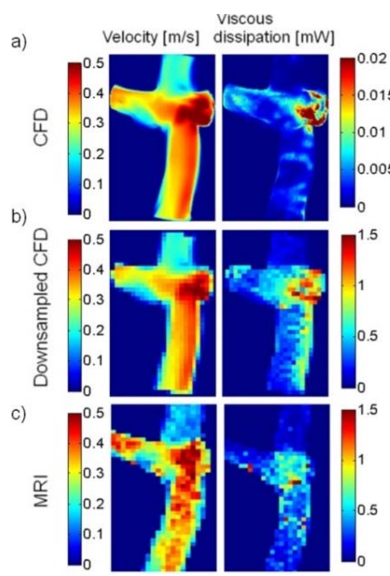
Target audience: Radiologists and researchers interested in hemodynamics and power losses related to the Fontan Circuit.

Purpose: Hypoplastic left or right heart syndrome, one of the most severe congenital heart diseases, typically requires multiple successive surgical interventions to reconstruct the cardiovascular system into a single ventricle physiology. The final surgical procedure creates the Fontan circulation which results in systemic venous return being supplied directly to the lungs through the pulmonary arteries without passing through the right ventricle [1]. Previous studies have suggested that reduced exercise capacity of Fontan patients might be associated with hemodynamic changes and specifically viscous dissipation related to complex flow patterns inside the Fontan circuit [2]. The ability to directly measure viscous dissipation in-vivo might therefore shed extra light on Fontan function and risk for impaired outcome in these patients. Typically, the calculation of viscous dissipation is performed using a control volume approach and solving the mechanical energy balance equation for the dissipation term [3]. This approach requires the measurement of pressure drop inside the Fontan circuit, which is obtained either by invasive measurements or computational fluid dynamics (CFD) simulations. Alternatively, the need for the pressure field can be bypassed by calculating viscous dissipation from the associated term of the Navier-Stokes equation [4]. The latter approach requires only the viscosity and the 3D velocity field, which can be noninvasively obtained by 4D flow MRI (time-resolved 3D phase contrast MRI with 3-directional velocity encoding). However, the results may be dependent on the spatial resolution since the dissipation term involves spatial derivatives of the velocity field. In this study, we aim to test the agreement between the two viscous dissipation measurement approaches and to investigate the influence of velocity spatial resolution on the viscous dissipation calculation. Thus, viscous dissipation was calculated inside the Fontan circuit with 3 different velocity fields: 1) subject-specific CFD velocities at high resolution, 2) CFD velocities down-sampled to MRI resolution and 3) 4D flow MRI velocities.

Methods: First, a steady state CFD simulation was performed for a straight tube with a diameter of 6.5mm and a length of 2 cm to check the agreement between two approaches. Inflow was set to 8.15 mL/s and prescribed with parabolic velocity profile. The density and the viscosity were set as 1.06 g/cm^3 and 3.5 cP (resulting Re =242). Viscous dissipation was then calculated analytically using the Poiseuille's law for the given setting and also by two approaches using CFD derived pressure and velocities. For the patient study, 4D flow MRI was performed in 6 Fontan patients (age: 9-21, 5 male) with whole heart coverage (spatial resolution: 1.9-2.5 x 1.9-2.5 x 2.2-3.3 mm^3, temporal resolution: 38.4-41.6ms, venc: 100-150 cm/s, TR: 2.36-2.72 ms, TE: 38.4-41.6 ms, flip angle=15°) using a 1.5 T system (Avanto or Aera, Siemens, Germany). The Fontan circuit was manually segmented on time-averaged phase contrast magnitude images using ITK-SNAP. All Fontan 3D segmentations were converted to volumetric meshes with an element size of 0.06 mm. Time resolved CFD simulations were performed with temporal resolution of 0.03 s using the velocities measured at inferior vena cava (IVC), superior vena cava (SVC) and right pulmonary artery (RPA) as in-flow boundary conditions. The left pulmonary artery (LPA) was prescribed as stress free. Blood density and the viscosity were assumed to be 1.06 g/cm3 and 3.5 cP, respectively. At the time point with highest inflow (sum of IVC and SVC flows), the CFD based velocities were interpolated to a grid with an isotropic resolution of 0.2 mm. These velocities were then down-sampled by averaging velocities within each voxel of a grid at MRI resolution, mimicking 4D flow MRI data [5]. Viscous dissipation was calculated from the velocities obtained from CFD, the down-sampled CFD data, and the MRI measurements. Dissipation at the wall was excluded by leaving the area outside the vessel undefined (NaN). The maximum intensity projection (MIP) of the velocities and the viscous dissipation were visualized for qualitative comparisons. Statistical significance was tested with two-sided paired t-test and p<=0.05 was chosen as significant.



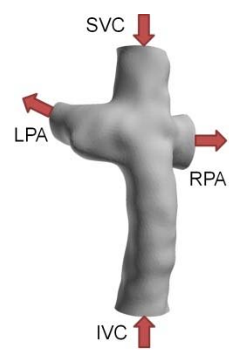


Figure-1: Velocities and viscous losses (Left and right columns respectively) obtained by a) CFD, b) down-sampled CFD and c) MRI. IVC, SVC, LPA and RPA and the orientation of the presented case are shown above.

Results and Discussion: The analytical viscous dissipation for the straight tube at the given setting was 6.6µW, which were accurately found by both approaches (6.5±0.1 µW). The 3D segmentation, MIPs of the various velocity fields, and the resulting viscous dissipation are shown for a representative case in Figure-1. The velocities and the viscous dissipation were generally larger at the T-junction. In regions containing uniform flow, such as IVC and SVC, the viscous losses were low. The MRI measured velocities (14.2±3.9 cm/s) and CFD based velocities (13.8±4.7 cm/s) were similar (p=0.64), but the down-sampled CFD velocities (9.9±3.8 cm/s) were smaller (p<0.01). The viscous dissipation based on CFD velocities (0.75±0.53 mW) was larger than that based on the down-sampled CFD velocities (0.26±0.21 mW) (p=0.01) and also that based on MRI velocities (0.39±0.23 mW) (p=0.05). The mean velocity and the viscous dissipation obtained for 3 different cases per patient are shown in Figure-2. Since CFD simulations were based on MRI measured flows, the magnitude and the distribution of velocities were similar. However, due to the lower resolution of MRI relative to CFD velocities, the viscous dissipation was expected to be underestimated when based on MRI velocities, as is shown by this data. The down-sampled CFD velocities resulted in further underestimation of viscous loss due to the combination of decreased velocities by intra-voxel averaging and decreased spatial resolution. In summary, the use of the viscous dissipation term of the Navier-Stokes equation to calculate viscous losses has the advantage of bypassing the need for pressure, but the tradeoff is that the losses are underestimated due to spatial resolution. Nevertheless, the relative viscous dissipation between subjects remained the same for all cases except one (shown in green, Figure-2b). This might be caused by the measurement errors and/or the MRI velocities used as boundary conditions.

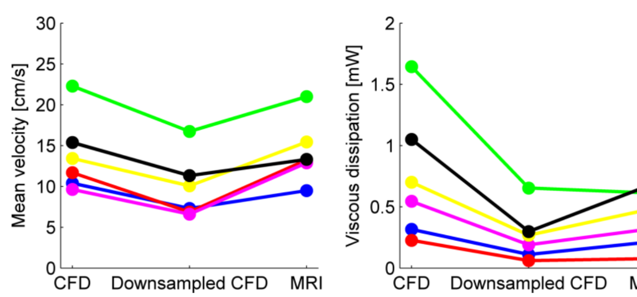


Figure-2: Mean velocity [cm/s] (left) and viscous dissipation [mW] (right) by using velocities of CFD, down-sampled CFD velocities and MRI measurements. Each color represents different subject.

Conclusion: Viscous dissipation was computed using CFD and 4D flow derived data. As expected, the computation of viscous dissipation was found to be dependent on resolution; however the relative differences were retained in 5 of the 6 cases.

References: 1-Gewillig M, et al. *Heart.* 2005; 91:839-846. **2-**Whitehead KK, et al. *Circulation* 2007; 116:I165-71.**3-**Bossers SM, et al. *Heart.*2014; 100:9 696-701. **4-**Barker AJ, et al. *Magn Reson Med*. 2014 Sep;72(3):620-8 **5-**Cibis M, et al. *NMR in Biomed.* 2014 Jul; 27(7):826-34