Improved full turbulence tensor quantification using ICOSA6 flow encoding for phase-contrast MRI

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Target audience: Researchers interested in hemodynamics, vascular disease or turbulence**.**

Purpose: Turbulence is an important factor in hemodynamics, and has been associated with several pathological conditions including energy losses and thrombogenic platelet deformations. Phase Contrast MRI (PC-MRI) has previously been used to quantify the three normal components of the turbulence stress tensor [1]. Quantification of the full turbulence tensor allows for more complex hemodynamic parameters such as pressure losses and shear stresses that has been linked to platelet activation. A suggested method to quantify the shear components is to subtract parts of two normal turbulence components from that obtained in the bisecting direction [2], but was found to suffer from low SNR due to the additive nature of noise. To decrease the error of the estimated turbulent shear, we propose using an ICOSA6 flow encoding regime [3] and calculate all turbulence components at once by phrasing it as a least-square-problem.

Methods: ANSYS CFX 14.5 was used to simulate constant flow through a rigid pipe with an unconstricted diameter of 14.6mm and a 75% cosine-shaped stenosis (reduction by area). Large Eddy Simulation (LES) was used to resolve turbulent flow fluctuations. To simulate Phase-contrast MRI, the data was re-gridded into 1.5 mm isotropic voxels using a 3D Gaussian point spread function. The re-gridded LES solution was divided into 20ms steps, and each time step was used to produce one line in k-space emulating a PC-MRI acquisition. Two different flow-encoding schemes were used: 1) Normals + bisecting (NB), and, 2) ICOSA6 (see Table 1).

For the NB encoding the normal components were calculated analogous to $\sigma_x^2 = \sigma_{v_1}^2 = -\frac{2}{|k_{v_1}|^2} ln\left(\frac{|S(k_{v_1})|}{|S(k_0)|}\right)$, where $k_v = \gamma\Delta M1$. The shear components are calculated analogous to $\sigma_{xy}^2 = \sigma_{v_4}^2 - \sigma_{v_1}^2/2 - \sigma_{v_2}^2/2$. For the ICOSA6 encoding the problem was formulated in a general form, $k_{enc,i}\sigma_{ij}^2 k_{enc,j} = -2ln\left(\frac{|S(k_{v_{enc}})|}{|S(k_0)|}\right)$, which was solved as a least-square problem for six directions simultaneously.

Normal noise was added to the individual encoding to evaluate the sensitivity of the normal and shear components to noise. The error was calculated as the root-mean-square error (RMSE) to the noise-free MRI simulation. A normalized RMSE (NRMSE) was obtained by dividing the RMS with the range of the components (average of the range obtained by NB and that obtained by ICOSA6).

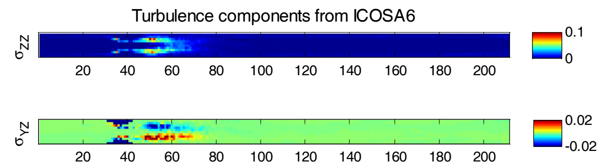

Figure 1: Example of normal and shear turbulence component acquired with ICOSA6.

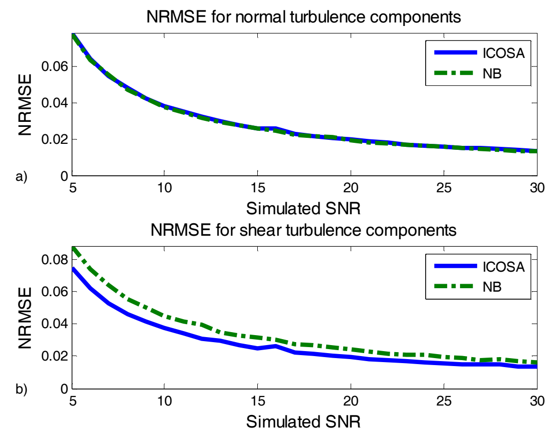

Figure 2: Normalized root-mean-square error for normal and shear turbulence

Results: Both NB and ICOSA produced turbulence tensors similar to those obtained by LES. The mean error for the normal turbulence components was similar for both methods (Figure 2a). The mean error for the shear components was smaller for the ICOSA6 encoding solved with least-square-minimization (Figure 2b).

Table 1: Flow encodings

Encoding	NB encoding	ICOSA6 encoding
0	0	0
1	ΔM1*x	ΔM1* (0.8507*x + 0.5257*y)
2	ΔM1*y	ΔM1*(0.8507*x - 0.5257*y)
3	ΔM1*z	ΔM1*(0.8507*y + 0.5257*z)
4	ΔM1*x + ΔM1*y	ΔM1*(0.8507*y - 0.5257*z)
5	ΔM1*x + ΔM1*z	ΔM1*(0.5257*x + 0.8507*z)
6	ΔM1*y + ΔM1*z	ΔM1*(0.5257*x - 0.8507*z)

Discussion/ Conclusion: The result shows that using an ICOSA6 flow encoding and determining the turbulence stress tensor by solving the lease-square-problem we are able to estimate turbulent shear components with lower noise sensitivity without compromising the result of the normal turbulence components.

References [1] Dyverfeldt et al, Magn Reson Med (2006) 56(4):850-8. [2] Elkins et al, Exp Fluids (2009) 46:285–296. [3] Zwart and Pipe, Magn Reson Med (2013) 69(6):1553-64