MRI Turbulence Quantification

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INTRODUCTION: Turbulent flow, characterized by velocity fluctuations, accompanies many forms of cardiovascular disease and may contribute to their progression and hemodynamic consequences. MR quantification of turbulence can be achieved by exploiting that presence of multiple spin velocities within a voxel reduces the MR signal magnitude under the influence of a bipolar gradient [1, 2]. MR turbulence measurements were recently successfully applied in-vivo [3] and an in-vitro study has demonstrated good agreement between turbulence quantities obtained by MRI and particle image velocimetry [4]. The objective of this study is to investigate potential pitfalls and sources of error in the quantification of turbulence using MRI.

MATERIALS AND METHODS: Different theoretical approaches [1, 2], including a two-point special case of Fourier velocity encoding, have arrived at similar expressions for the relationship between the turbulence intensity, σ, and the MR signal magnitude, $|S(k_v)|$:

$$\sigma = sqrt\left[\ln\left(|S(0)|/|S(k_v)|\right)\right]/k_v . \quad \text{[Eq. 1]}$$

In Eq. 1, k_v describes the turbulence sensitivity of the applied gradient waveform and is proportional to the first gradient moment of the bipolar gradient. Computation of σ requires at least two measurements of $|S(k_v)|$. In the two-point case, data necessary for computing σ can be provided by a standard PC-MRI data acquisition where the velocity encoding range (VENC) corresponds to π/k_v [2]. When more than two k_v factors are applied, a least-squares fit of the measurement points can be carried out to compute σ [1].

Theoretically, MR turbulence measurements are affected by intravoxel spin velocity variations due to non-turbulent phenomena such as spatial velocity gradients. Here, the extent to which this may deteriorate turbulence quantification was investigated by using an MR simulation approach based on a numerical flow phantom obtained by large eddy simulations in a stenotic pipe.

The impact of noise on the dynamic range of MR turbulence measurements was investigated by means of a simulation approach in which noise was added to a theoretically ideal MR signal. Mean and standard deviation values were generated from 100000 signals. When scan time is not a critical issue, multiple acquisitions of S, with the same k_v or with a range of k_v values, can be performed. The effect of noise on the dynamic range will depend on the chosen approach. Here, three different approaches were evaluated: standard least-squares fit using multiple k_v values, weighted least-squares fit using multiple k_v values, and multiple measurements using the same k_v value (signal averaging).

RESULTS AND DISCUSSION: Flow phenomena other than turbulence were found to have a minor effect on MR turbulence measurements. Although the greatest velocity gradients in the numerical flow phantom were about 500 [s^{-1}], the contribution to the measured turbulence intensity was less than 3% of $1/k_v$, which defines the σ value with best accuracy. This confirms recent in-vivo observations [2] and suggests that the effects can be neglected.

The impact of noise on the dynamic range of MR turbulence measurements is outlined in Fig. 1. When noise dominates the measured signal, the Rician distribution of MR magnitude data results in an overestimation of $|S(k_v)|$ (Fig. 1a) and, consequently, an underestimation of σ (Fig. 1b). Best accuracy is obtained at $\sigma = 1/k_v$ (circle). An estimation of the σ value at which noise on average dominates the measured signal can be obtained by replacing $|S(k_v)|$ in Eq. 1 with the mean magnitude of the noise (Fig. 1b, dashed line).

Different approaches for utilizing additional scan time and their effects on the dynamic range are shown in Fig. 2. As compared to the standard two-point case, which is included as a reference, signal averaging of $S(k_v)$ and weighted least-squares fitting extend the dynamic range whereas a standard least-squares approach has the opposite effect. Not shown here, the greatest increase in accuracy at the central part of the dynamic range is obtained by the signal averaging approach. Thus, when the σ values of interest can be reasonably approximated, signal averaging using the same k_v value is the best option. Otherwise, weighted least-squares fitting using a range k_v values may be helpful.

CONCLUSIONS: We have investigated potential pitfalls and sources of error in MR turbulence measurements and outlined strategies for acquiring data suitable for turbulence quantification. The effects of non-turbulent flow phenomena were found to be negligible. By appreciating that the k_v parameter is best chosen so that values σ values of interest are close to $1/k_v$, robust and accurate estimates of turbulence intensity can be obtained from a standard PC-MRI measurement. The findings reported in this work may enhance the applicability of MR methods for turbulence quantification.

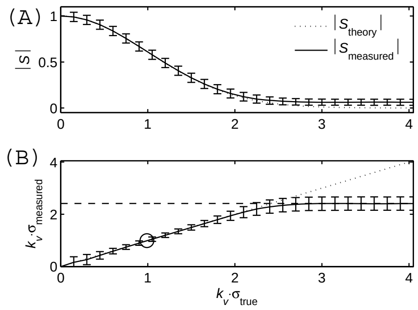

Figure 1. The impact of noise on the dynamic range of MR turbulence measurements. A: As compared to the theoretic relation (dotted line), the measured signal (solid line) is on averaged overestimated at low SNR. B: Consequently, estimates of turbulence intensity are underestimated if too much turbulence sensitivity (k_v) is applied in relation to the turbulence intensity of the flow being studied. The error bars show the uncertainty in the estimates of $|S_{\text{measured}}|$ and σ due to noise (bar height = ± one standard deviation). Circle: $\sigma_{\text{true}} = 1/k_v$.

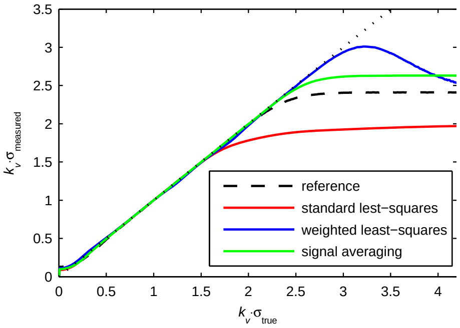

Figure 2. Comparison between different approaches for utilizing additional scan time and their effects on the dynamic range. The two-point approach without signal averaging, as used in Fig. 1b, is included as a reference (dashed line). Note that only the mean values are shown.

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