Optimisation of velocity encoding gradients for phase contrast gas velocity taking diffusion into account.

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Introduction

Phase contrast MRI which is commonly used to map blood **[1]**has been applied more recently to map gas velocities using hyperpolarized tracers**[2, 3]**.The bipolar gradient used to induce a phase shift proportional to velocity also introduces diffusion weighting. This can be safely neglected considering diffusion coefficients of liquids. However, for a gas, diffusion can no longer be neglected **[3]**. As an illustration on helium, considering an encoding time of 10ms for spins moving at 20 cm.s^{-1}, the displacement (2mm) becomes the same as the mean diffusion length. Blurring is introduced and a loss of precision in the phase measurement is obtained. While the precision on the velocity measurement can be enhanced by increasing the gradient 1st moment, there is a competition with the loss introduced by diffusion weighting. Here, considering both phenomena, we derive theoretically and verify experimentally the bipolar gradient characteristics for an optimized velocity measurement.

Theory

After a bipolar gradient, velocity error is given by: $\sigma_v = \frac{\sigma}{2\pi I_0}\frac{FOS}{A}$ **[4]** where σ is the noise standard deviation, I_0 the signal intensity, FOS is the field of speed characterizing the velocity encoding and *A* the attenuation induced by diffusion within the bipolar gradient**[5]**. For a fixed TE, we can determine velocity error as a function of the FOS. The optimal *FOS* is thus:

$$FOS_{opt} = \pi\sqrt{\frac{2D}{T}}$$

and depends on the length of the bipolar gradient (*T*) and the diffusion coefficient (*D*) of the buffer gas **[6]**. Figure 2, presents these theoretical curves.

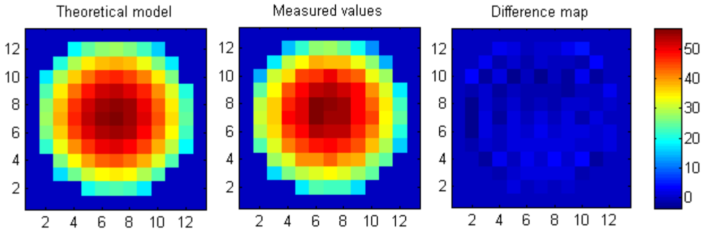

Figure 1: Theoretical model (paraboloid), reconstructed velocity map and difference for ^{4}He with FOS = 200 cm.s^{-1}

Material and methods

Data were acquired at 1.5T. ^{3}He was hyperpolarized on site and mixed within different buffer gases to change the diffusion coefficient in a controlled way. Three vector gases were used, ^{4}He, N_2 and SF_6. The mixture flowed through a 3m long straight tube (Ø = 34 mm) at a constant rate (controlled by a volumetric pump) with a mean velocity of 20 cm.s^{-1} ensuring a laminar and parabolic flow. The 2D gradient echo sequence was flow-encoded through plane with the following parameters, FOV = 50*60*50 mm, pixel = 2.5*2.5 mm, α = 20° and TR/TE = 16/6.0 ms. The sequence was repeated 6 times varying the bipolar gradients amplitudes with a constant time corresponding to FOS from 50 cm.s^{-1} to 200 cm.s^{-1}. Data were reconstructed and processed using Matlab®. A paraboloid was fitted to each velocity map using the experimental mean velocity (V_m). The SD of velocity (σ_v) was calculated on the central 85% of the tube section from the difference between the experimental values and the model values.

Results

The theoretical model, the measured values and the differences are shown in Figure 1 for ^{4}He with FOS=200 cm.s^{-1}. The bias between theoretical V_m and the measured V_m were: for ^{4}He, ΔV_m=-10 cm.s^{-1}; for N_2, ΔV_m=-0,5 cm.s^{-1}; for SF_6, ΔV_m=7,4 cm.s^{-1}. Figure 2 shows, for each gas, the theoretical curve of velocity error (σ_v) as a function of FOS with the theoretical optimal point and the 6 experimental points (each experimental value was corrected for the amount of polarized gas that was used).

Discussion

The observed biases between flows measured by MR and by external flowmeter may be due to the difficulty of measuring flows with various gas mixtures. This bias does not hinder the study, which focuses on velocity measurement precision. Figure 1 shows that we can measure and reconstruct a velocity map very close to a theoretical paraboloid. In Figure 2, big FOS imply an important velocity error because the velocity encoding is less efficient and reducing the FOS corrects it. It would be the same with blood. However, in our case, in spite of continuing to diminish with the FOS, velocity error reaches a minimum and then rises again while the FOS diminishes. This effect is due to the diffusion weight growing with little FOS. These results validate our theoretical computations and present experimental minima not so far from theoretical ones. For better results, these experiments should be continued with more experimental points.

Conclusion

We have derived a theoretical expression to adjust the FOS and obtain an optimal velocity measurement for phase contrast MRI on a gas. This optimal value is proportional to the square root of the ratio of the diffusion coefficient to the gradient application time. While traditional phase contrast on liquids will decrease the FOS to increase the precision with virtually no limit, theoretical and experimental data show here that for gas, diffusion becomes rapidly dominant and the corresponding signal attenuation then limits the expected velocity precision. Even though preliminary, the presented results are readily usable to define the optimal bipolar gradient parameters for velocity measurement phase contrast on hyperpolarized gas.

References: **1**. Srichai et al. AJR Am J Roentgenol, 2009. 192(3): p. 662-75. **2**.de Rochefort et al. Magn Reson Med, 2006. 55(6): p. 1318-25. **3**. Minard et al. J Magn Reson, 2008. 194(2): p. 182-91. **4**. Conturo et al. Magn Reson Med, 1990. 15(3): p. 420-37. **5**. Torrey. Phys rev, 1956. 104(3): p. 563. **6**. Stejskal et al. J Chem Phys, 1965. 42: p. 288-92.

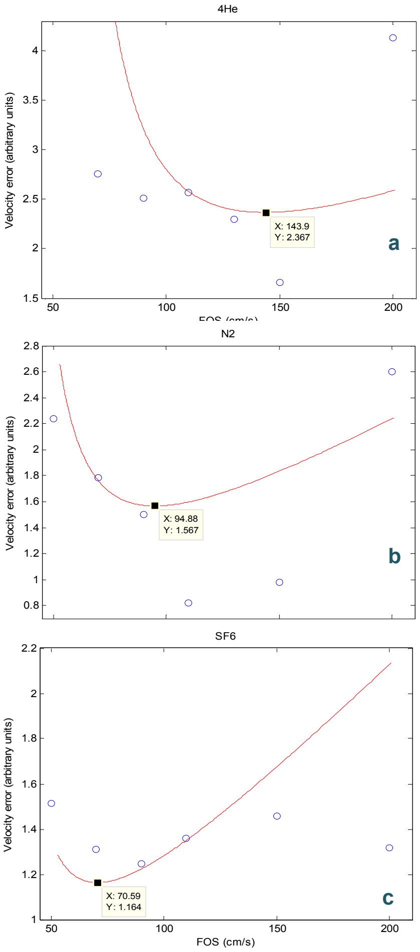

Figure 2: Velocity error and FOS for theoretical curves with optimal points and experimental points for ^{4}He (**a**), N_2(**b**) and SF_6 (**c**)