Reliability and sensitivity of intravoxel incoherent motion (IVIM) MRI in measuring cerebral perfusion

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Introduction

Intravoxel incoherent motion (IVIM) MRI [1] is a technique proposed for concurrent measurement of diffusion and perfusion. In IVIM MRI, signals are measured with multiple b-values and modeled as a weighted sum of two exponential decay functions on a basis of two assumptions. First, capillaries are randomly oriented such that microvascular blood flow can be viewed as pseudo-diffusion that is faster than interstitial water diffusion. Second, pseudo-diffusion and diffusion are both Gaussian. IVIM MRI has been applied to various parts of human body [2] although references are scarce [3,4] regarding its reliability and sensitivity. In this study, we investigated the sensitivity of IVIM MRI in the brain by comparing with arterial spin-labeling (ASL) MRI. Monte Carlo simulation was performed to assess the reliability of the perfusion indexes derived from nonlinear fitting.

Materials and Methods

1. Monte Carlo simulation. According to Le Bihan et al [1], the signal of IVIM MRI is described by Eq. [1]: $S(b)/S_0 = f\exp(-bD^*) + (1 - f)\exp(-bD)$ where $S(b)$ and S_0 are the signals obtained with and without diffusion encoding, respectively; D^* and D are the pseudo-diffusion coefficient and diffusion coefficient, respectively; f is the volume fraction of intravascular space. By using 13 b-values (0,10,20,30,40,50,100,250,400,550,700, 850,1000 s/mm^2), in accordance with our experimental parameters, theoretical signals were generated for varied f (from 0.01 to 0.10 in steps of 0.01) and D^*/D ratio (from 1 to 50 in steps of 1). D was assumed to be 6×10^{-4} mm^2/s (~gray matter). Gaussian noise was added to the theoretical signal with the signal-to-noise ratio at the largest b-value (SNR_{b1000}) ranging from 10 to 100 in steps of 10. We estimated D by fitting $\exp(-bD)$ to the noise-corrupted data of b = 400-1000. Based on the estimated D, Eq. [1] was then fitted to the noise-corrupted data of b = 0-400 to estimate D^* and f. For each combination of $f/D^*/SNR_{b1000}$, 100 estimates were obtained and calculated for their mean and standard deviation.

2. MR imaging. The Institutional Review Board approved this study. Seven healthy volunteers (age = 22-33 yrs) were imaged and each gave written informed consent beforehand. All imaging was performed on a 3T Siemens system using the body coil transmitter and a 12-channel phased-array receiver. For IVIM imaging, a spin-echo echo-planar readout was used (TR = 2 s, TE = 100 ms, x2 GRAPPA acceleration, matrix = 128x128, above-mentioned b-values along 3 orthogonal directions, 4 averages). ASL imaging was based on pseudocontinuous labeling (labeling duration = 2 s, post-labeling delay = 1.5 s) and a gradient-echo echo-planar readout (TR = 4.3 s, TE = 15 ms, matrix = 64x64, 6/8 partial Fourier). Twelve axial slices (FOV = 20 cm, slice thickness = 5 mm) were prescribed with the center slice at the level of the corpus callosum.

3. Data analysis. Maps of D, D^*, and f were derived for each direction of diffusion encoding separately and then averaged. ASL images were pair-wise subtracted, averaged, and converted into quantitative flow maps. ASL-derived flow maps were interpolated to 128x128 and coregistered to the average IVIM images. A mask was generated to include voxels where the probability of gray matter was above 0.8 and the overall R^2 of $D/D^*/f$ fitting was above 0.9. Within the mask, f and the product of f and D^* were correlated with ASL-derived flow values. R^2 was also inspected within areas that predominantly contained white matter.

Results and Discussion

Figure 1 shows the dependence of IVIM-derived perfusion indexes on D^*/D ratio, f, and SNR. The indexes are less reliable when D^* and f are small (particularly when $f < 0.05$ and D^*/D ratio < 10). Overall, f is more robust an index than D^*. ASL-derived blood flow values were found mildly correlated with fD^* and f. The correlation, however, started to diminish when blood flow was below 40 or above 80 ml/100ml/min. The R^2 was lower in white matter than in gray matter (1st quantile = 0.72 vs. 0.89, median = 0.83 vs. 0.94, 3rd quantile = 0.90 vs. 0.96). This could be because blood volume is smaller in white matter where the assumption of Gaussian diffusion may not be appropriate [5]. At last, SNR is critical for reliable fitting results.

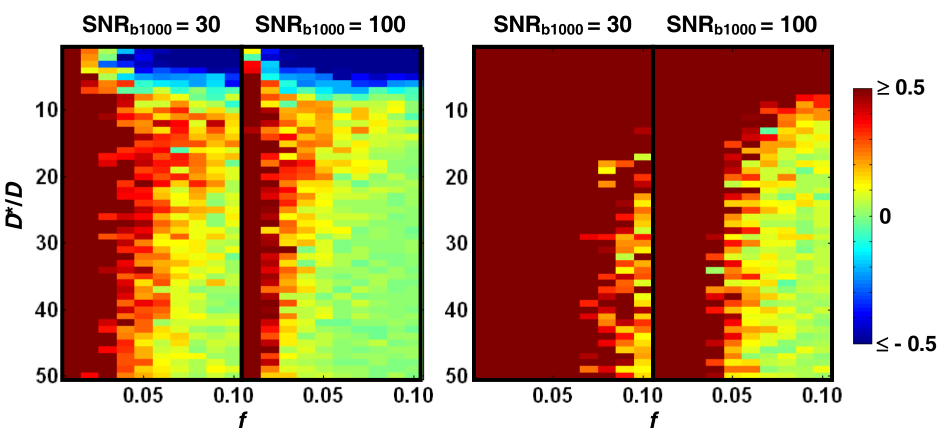

Figure 1. Measurement variability at varied D^*/D ratio, f, and SNR. Color-coded are results of (estimated value – theoretical value) / theoretical value. Left and right panels are the results of f and D^*, respectively.

References 1. Le Bihan D, et al., Radiology 1988;168:497-505. 2. Takahara T and Kwee TC, JMRI 2012;35:1266-1273. 3. Federau C, et al, Radiology 2012;265:874-881. 4. Neil J, et al, MRM 1994;32:60-65. 5. Alexander DC, et al, MRM 2002;48:331-340.