Simultaneous measurement of cerebral blood volume and diffusion heterogeneity using two-compartment-model-based diffusion kurtosis imaging

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Introduction

Cerebral diffusion and perfusion are closely associated with brain physiology. Abnormal change of these physiological parameters may be both the cause and the consequence of neurological diseases. Based on the assumption that the random motion of water molecules follows the Gaussian distribution, water diffusivity can be estimated in terms of apparent diffusion coefficient, an index derived from diffusion-weighted MR imaging [1]. However, several studies [2,3] have shown that the assumption may not be entirely accurate in biological tissues composed of complex microstructure. In this study, we described a method for simultaneous measurement of cerebral blood volume and diffusion heterogeneity by combining diffusion kurtosis (DK) imaging [3] with a two-compartment model.

Theory

Following the model proposed by Le Bihan [4], the signal decay caused by diffusion weighting (quantified by b-value) can be considered as a composite outcome of interstitial water diffusion (characterized by diffusion coefficient D) and microvascular blood flow (characterized by pseudo-diffusion coefficient D*):

$$\frac{S(b)}{S_0} = f\exp(-bD^*) + (1-f)\exp(-bD) \qquad [1]$$

where S_0 is the signal measured with b = 0 and f is the volume fraction of microvasculature (and thus proportional to cerebral blood volume). For our purpose, two modifications were made to equation [1]. First, considering the high variability in D* estimate [5], we acquired data using 400 s/mm^2 as the smallest non-zero b-value such that the first term on the right side can be neglected. Second, diffusion kurtosis coefficient (K) [3] was introduced to the second term. Equation [1] thus becomes:

$$\frac{S(b)}{S_0} = (1-f)\exp\left(-bD + \frac{1}{6}b^2D^2K\right) \qquad [2]$$

Materials and Methods

A. Simulation Computer simulations were performed to assess the precision and accuracy of our model at varied levels of signal-to-noise ratio (SNR, ranging from 16 to 1024 in powers of 2, based on S_0 and Rician noise). For each condition, 1000 random samples were generated and 1000 estimates of K/D/f were obtained. Coefficient of variation (CV) was calculated.

B. MR Imaging The Institutional Review Board approved this study. Fifteen healthy adult volunteers were recruited and imaged on a 3T clinical scanner (Tim Trio, Siemens). Written informed consent was obtained from each participant beforehand. Diffusion encoding was applied along three orthogonal directions in separate series (single-shot twice-refocused spin-echo echo-planar readout). Imaging parameters were: TR = 2.2 s, TE = 104 ms, FOV = 20 cm, matrix = 128x128, slice thickness = 5 mm, b = {0,400,550,700,850,1000,1400,1700} s/mm^2, 12 repetitions after 1 dummy scan. Bootstrap was performed to assess measurement variability.

Fig 1. Error bars = S.D. of 1000 samples. Dotted lines = theoretical values.

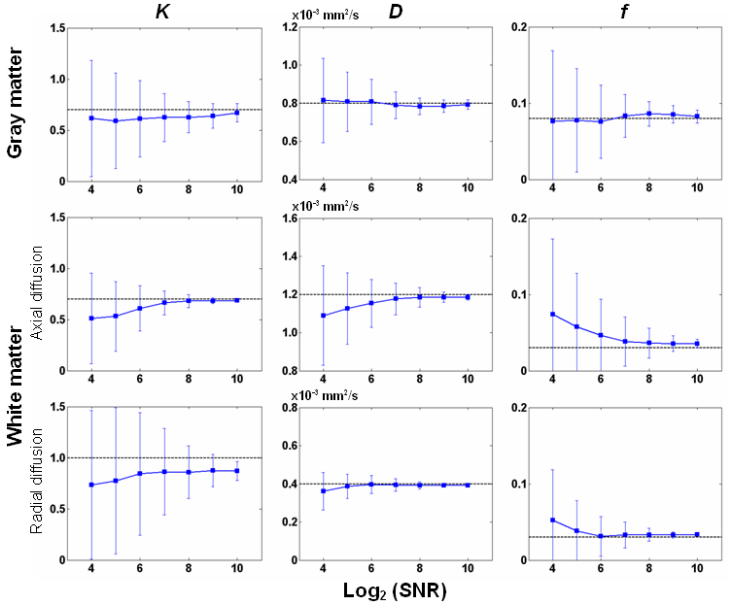
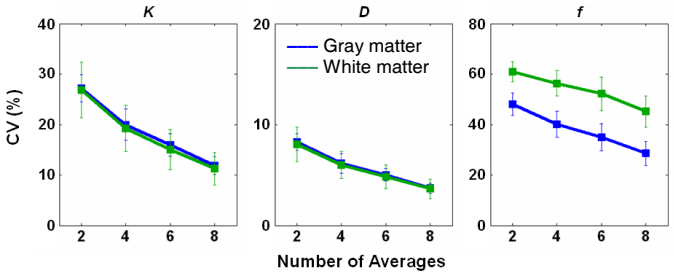


Fig 2. Bootstrap results. Error bars = S.D. of 15 subjects.



Results and Discussion

As shown in **Fig 1** (numerical data), precision increases when SNR increases. D is more robust against noise than K and f. Let's consider SNR = 64-128 (approximately the range in our experimental data; scan time ~12 min). The average error and variability are ~5% and ~10% for D estimate, ~10% and ~50% for f estimate, and ~15% and ~30% for K estimate. **Fig 2** shows the bootstrap results. Note that the indexes were estimated for 3 orthogonal directions of diffusion encoding separately and then averaged, which reduces the variability by a factor equal to the square root of 3. Measurement variability is notably smaller for D (< 10%) as compared with K and f. By extrapolating the plots, the coefficient of variation is about 10% for K, 3% for D, and 30% for f (20% in gray matter and 40% in white matter) when the number of averages is 12, which reasonably agrees with the numerical results.

References

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