Improved Robustness with a Stretched Exponential Model for Intravoxel Incoherent Motion (IVIM) DW Signal

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INTRODUCTION

Background: Le Bihan et al (1) proposed using diffusion-weighted imaging (DWI) based on intravoxel incoherent motion (IVIM) to distinguish pure molecular diffusion and microcirculation, or blood perfusion, by acquiring DW data with the diffusion sensitivity parameter b at low values (<200 s/mm^2) and at high values (>200 s/mm^2). Le Bihan et al (1) fit a two compartment bi-exponential model to IVIM data while Bennett et al (2) fit a stretched exponential model (for high b-values). The models are:

Bi-exponential model:

$$S(b) = S(0)\left[(1-f)e^{-bD} + fe^{-bD^*}\right] \quad [1]$$

D^* is the pseudo-diffusion coefficient, [mm^2/s]

D is the diffusion coefficient, [mm^2/s]

f is the fraction of total volume of blood moving in the voxel compared to the total voxel volume [%].

Stretched Exponential (Kohlrausch decay function): The Kohlrausch decay function allows gauging in a simple way the deviations from the "canonical" single exponential.

$$S(b) = S(0)e^{-bDDC^{\alpha}} \quad [2]$$

DDC is the distributed diffusion coefficient,

α is a dimensionless "stretching" parameter between 0 and 1 that characterizes deviation of the signal attenuation from monoexponential form.

MATERIAL AND METHODS

Simulations: Monte Carlo (MC) simulations were performed to determine confidence in parameters derived from BE and SE analysis of IVIM DWI data.

- The number of MC trials was 10,000.
- Ideal signal intensity data simulated using BE parameters obtained from the literature (3). For healthy renal cortex: D^* = 11.8×10^{-3} mm^2/s; D = 1.5×10^{-3} mm^2/s; f = 38%.
- We are aware of no prior literature on SE (IVIM) parameters, so the following parameters were chosen (through least-squares fitting) to replicate BE data: DDC = 2.9×10^{-3} mm^2/s, α = 0.7.

MR Imaging:

All studies were performed on a 3.0 T unit (Signa; GE Healthcare, Milwaukee, WI). Data were acquired with a pelvic eight-channel phased-array coil from a spherical phantom filled with a solution of non-dairy creamer. Diffusion parameters include the following: b values of 0, 10, 30, 40, 50, 80, 100, 200, 400, 500 s/mm^2; TR/TE of 2000/66.5 ms; [FOV] of 24×24cm^2, slice thickness of 4 mm, total acquisition time of 3 minutes. In-vivo data were acquired from the kidney's of N healthy adults using a phased-array coil and the same protocol used for the phantom study.

RESULTS

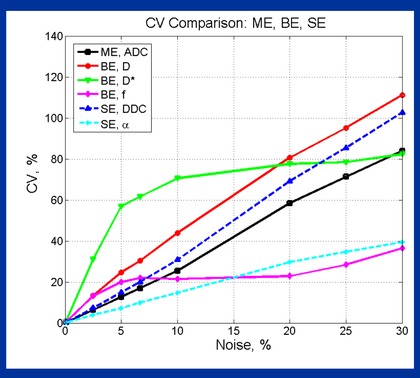
Fig. 1 presents the results of our simulation and demonstrates the potential advantages of the SE model. As expected, the bias and CV of , which describes the pseudo-diffusion caused by perfusion effects, increases rapidly with noise. In comparison, and α have tolerable CV (<15% at 5% noise) and bias (absolute bias< 11% at 5% noise).

Fig. 2 is a typical plot of *in vivo* data and the corresponding BE and SE fits, map of *DDC* and *α* in Eq. [1]. Characteristic of the SE function is the existence of two regimes: a faster-than-exponential (with respect to an exponential of lifetime 1/DDC) initial decay at b<1/DDC, and a slower-than-exponential decay for b>1/DDC. These two regimes are well-distinguished for small α, but become indistinct as $\alpha \longrightarrow 0$.

- The main advantage of the SE model is its excellent stability to noise.
- The disadvantage is the extension of this robustness: the model is quite rigid and may not describe data as well as other models. Of particular concern is its infinite slope at b0.
- Further investigations are under way to
  1) optimize SE acquisition,
  2) estimate confidence and variance of fitted parameters.

Simulations:

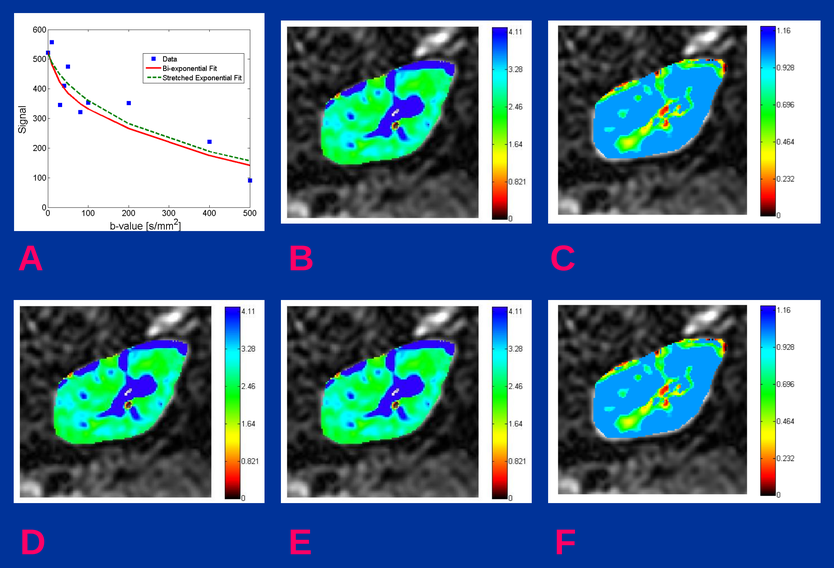
- *Precision* of each parameter was characterized by its coefficient of variation (CV), defined as the ratio of the parameter's standard deviation to its mean.
- *Accuracy* was assessed by the relative bias, defined as a percentage difference between the fitted and ideal parameter values.



A B

Fig. 1: MC simulations of (**A**) precision (CV) and (**B**) accuracy (bias) of parameters vs (Rician) noise of monoexponential (ME) model BE model, and SE model.

MR Imaging:



A B C

D E F

Fig. 2: (**A**) Plot of vs b [s/mm^2] with BE and SE model fit for *in vivo* data. (**B**) Map of DDC, and (**C**) α, (**D**) D^*, (**E**) D, and (**F**) f.

DISCUSSION

The ability of IVIM to provide sensitive and specific values for the bi-exponential (BE) model is severely limited due to:

1. The narrow range of relevant b-values associated with pseudo-diffusion in the faster diffusion component (i.e., the large slope of $\ln(S(b))$ vs. b)
2. The high degree of signal variability in low b-value measurements.

REFERENCES

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