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

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INTRODUCTION

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 sec/mm$^{2)}$ and at high values (>200 s/mm^2). 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) and 2) the high degree of signal variability in low b-value measurements. We propose the stretched exponential (SE) model, previously considered for modeling high b-value data (2), as an alternative to describe IVIM diffusion signal.

THEORY

SE (Kohlrausch decay function) model for IVIM: The Kohlrausch decay function allows gauging in a simple way the deviations from the "canonical" single exponential: $S(b) = S_0 e^{-(b\times DDC)^{\alpha}}$ [1]
where DDC is the distributed diffusion coefficient and α is a dimensionless "stretching" parameter between 0 and 1 that characterizes deviation of the signal attenuation from monoexponential form.

MATERIALS AND METHODS

Simulations: Monte Carlo (MC) simulations were performed to determine confidence in parameters derived from BE and SE analysis of IVIM DWI data. Ideal signal intensity data simulated using BE parameters obtained experimentally by Zhang et al (3) for healthy renal cortex were $D^* = 11.8\times10^{-3}$ mm^2/s; $D = 1.5\times10^{-3}$ 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: $DDC = 2.9\times10^{-3}$ mm^2/s, α= 0.7. The number of MC trials was 2000. The *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.

Phantom and In-Vivo Studies: 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 a healthy volunteer using a phased-array coil and the same protocol used for the phantom study.

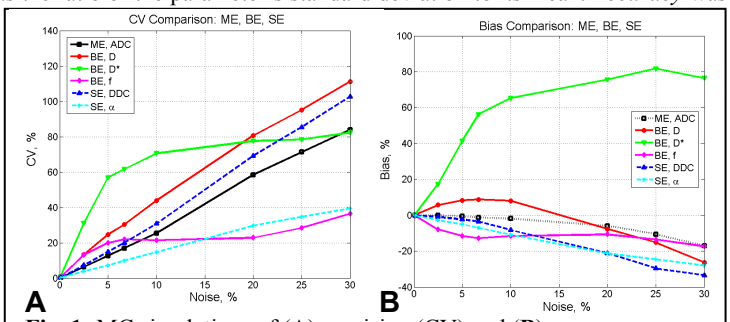

Fig. 1: MC simulations of (**A**) precision (CV) and (**B**) accuracy (bias) of parameters vs (Rician) noise of monoexponential (ME) model (ADC), BE model (D^*, D, f), and SE model (DDC, α) model.

RESULTS AND DISCUSSION

Fig. 1 presents the results of our simulation and demonstrates the potential advantages of the SE model. As expected, the bias and CV of D^*, which describes the pseudo-diffusion caused by perfusion effects, increases rapidly with noise. In comparison, DDC 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 $\alpha \to 1$. 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 b→0. Further investigations are under way to 1) optimize SE acquisition, 2) estimate confidence and variance of fitted parameters.

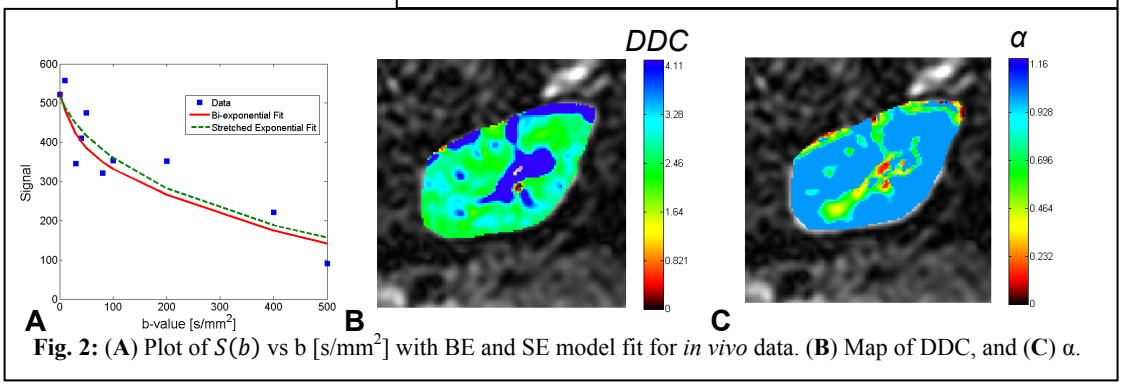

Fig. 2: (**A**) Plot of $S(b)$ vs b [s/mm^2] with BE and SE model fit for *in vivo* data. (**B**) Map of DDC, and (**C**) α.

REFERENCES

[1] Le Bihan D, et al. Radiology. 1988;168(2):497-505. [2] Bennett KM, et al. Magn Reson Med. 2003;50(4):727-34. [3] Zhang JL, et al. ISMRM 2009; p. 4110.