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:

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

$D^*$ 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.

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

$D\alpha$ is the distributed diffusion coefficient, $\alpha$ is a dimensionless “stretching” parameter between 0 and 1 that characterizes deviation of the signal attenuation from monoexponential form.

MR Imaging:

All studies were performed on a 3.0 T unit (Sigma; 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 24x24cm$^2$, 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 $S(b)$, which describes the pseudo-diffusion caused by perfusion effects, increases rapidly with noise. In comparison, $D\alpha$ 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 $D\alpha$ and $D$ 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 $1/D\alpha$) initial decay at $b < 1/D\alpha$, and a slower-than-exponential decay for $b > 1/D\alpha$. These two regimes are well-distinguished for small $\alpha$, but become indistinct as $\alpha \rightarrow 0$.

- 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 $b = 0$.
- 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.

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: $D^* = 11.8 \times 10^{-3}$ mm$^2$/s; $D = 1.5 \times 10^{-3}$ 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: $D\alpha = 2.9 \times 10^{-3}$ mm$^2$/s, $\alpha = 0.7$.

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