Monte Carlo Simulation of Muscle Diffusion: Effect of SNR

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Introduction

Diffusion-tensor MRI (DT-MRI) is a promising tool for micro- and macro-structural characterization of striated muscle. For example, the eigenvector (ε_1) corresponding to the first eigenvalue (λ_1) is coincident with the local muscle fiber orientation (1), enabling fiber tracking applications (2, 3); also, the second and third eigenvalues (λ_2 and λ_3, respectively) appear to be differentially sensitive to muscle damage and microstructure (4). Muscle DT-MRI is made challenging, however, by the lower T_2, lower fractional anisotropy (FA), and larger diffusivities in muscle than in white matter. These issues suggest that more stringent signal-to-noise ratio (SNR) requirements may exist for muscle than for white matter DT-MRI studies. Moreover, partial volume artifacts due to intramuscular fat deposition require the development of fiber tracking algorithms that can identify proper fiber trajectories around these depositions on the basis of parameters such as T_2-weighted signal, FA, and $\lambda_{1\text{-}3}$. Therefore, the purpose of this study was to use Monte Carlo simulations to examine the dependence of the muscle and fat diffusion tensors and derived indices on SNR, in order to guide the future development of muscle DT-MRI fiber tracking algorithms.

Methods

Monte Carlo Simulations: A total of 10,000 independent simulations (1000 trials at each of 10 SNR levels) were conducted as follows. A model tissue was defined having 100×100 muscle elements and 100×100 fat elements, with each element representing a 60×60 μm area. Muscle elements were defined as having λ_1=2.1×10^{-3} mm^2/s; λ_2=1.6×10^{-5} mm^3/s; λ_3=1.2×10^{-3} mm^2/s (Trace/3≡1.633×10^{-3} mm^2/s; FA≡0.2691) and to have $\varepsilon_{1\text{-}3}$ lying respectively along the X, Y, and Z axes. The muscle T_1/T_2/water proton density (ρ) values were 1200 ms/35 ms/0.8 AU, respectively. Fat elements were defined as having λ_1=λ_2=λ_3=0.6×10^{-3} mm^2/s (5) with their eigenvectors randomly assigned to lie along the X, Y, or Z axes with equal probability. The fat T_1/T_2/ρ values were 500 ms/200 ms/0.1 AU. For each tissue element, the diffusion tensor was calculated as $\mathbf{E}^T\cdot\mathbf{L}\cdot\mathbf{E}$, where **E** is a 3×3 matrix of eigenvectors, **L** is a 3×3 matrix with eigenvalues along the diagonal elements and zeroes in the off-diagonal elements, and the superscript T indicates the transpose operation. Images were generated at 1.2×1.2 mm in-plane resolution (20×20 tissue elements per image pixel). A fat saturated, T_2-weighted image was calculated using TR/TE=5000/45 ms and b=0 s/mm^2. After averaging the diffusion tensor across the 20×20 tissue elements, pixel intensities in diffusion-weighted images were calculated using TR/TE=5000/45 ms and b=500 s/mm^2 applied along 10 directions as defined by Jones (6). Two channels of Gaussian noise (1 real, 1 imaginary) were generated, expressed as a complex number, and the magnitude added to the images to create measured SNR levels ranging from 27.3-415.2 for pixels containing muscle and 10.8-152.5 for pixels containing fat (see **Results**). For each pixel, $\lambda_{1\text{-}3}$ and $\varepsilon_{1\text{-}3}$ were obtained by diagonalizing the DT matrix and magnitude-sorting the eigenvalues.

Data Analysis: For each of the *J*=1000 model trials per SNR level, the angular deviation (θ) between $\varepsilon_{1,j}$ and the mean value of ε_1 for all 1000 trials (ψ_1) was determined as (7):

$$\theta = \text{acos}\left(\varepsilon_{1,j}\cdot\psi_1\right)$$

The mean and standard deviation (SD) for the estimates of $\lambda_{1\text{-}3}$, FA, and θ were calculated at each of the noise levels.

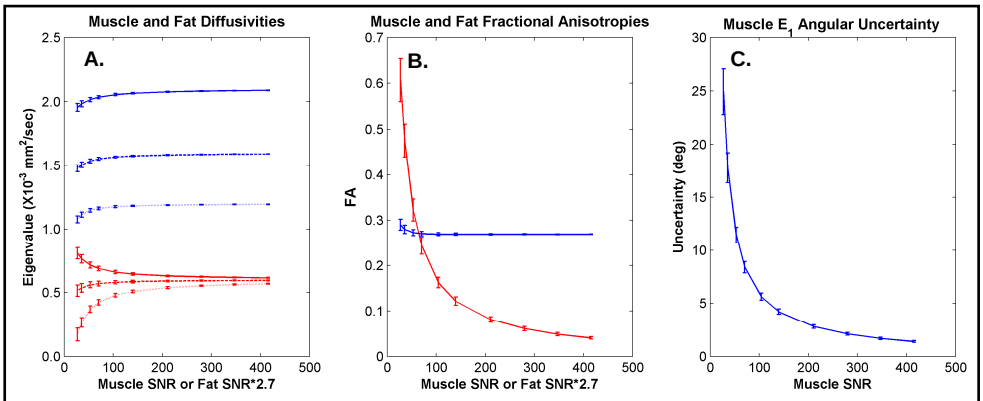

Figure 1. Results of Monte Carlo simulations at muscle SNR levels ranging from 27-415. Mean, SD are shown. A. First, second, and third eigenvalues for muscle (blue lines) and fat (red lines). Fat SNR was ~2.7-fold lower than muscle SNR. B. Fractional anisotropy for muscle (blue line) and fat (red line). C. Angular uncertainty of the first eigenvector of the muscle diffusion tensor.

Results and Discussion

Figure 1 shows the dependence of $\lambda_{1\text{-}3}$, FA, and θ on SNR. For values of SNR>50, $\lambda_{1\text{-}3}$ and FA were within 5% of the known values. Fat FA decreased significantly with increasing SNR, and within the range of typical SNR values (60-100) the fat and muscle FA values were similar. Linear interpolation of θ between successive SNR values suggests that θ<10º occurs at SNR=60 and that θ<5º occurs at SNR=119.

Conclusions

The need to detect small differences in muscle transverse diffusivities and to accurately specify fiber orientation creates high SNR requirements for muscle DT-MRI studies. The similarity of the muscle and fat FA values within the range of typical SNR values precludes the use of this variable in fiber tracking algorithms designed to track muscle fiber trajectories in the presence of fat-muscle partial volume artifacts.

References

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