Initial Performance of the Diffusive Quantitative Imaging Phantom (DQIP): Thermal and SNR Characteristics Using a Clinical Protocol

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Target Audience:
Any medical professional from an ACR accredited facility utilizing diffusion-weighted MRI techniques in standard of care will benefit from this study.

Purpose:
Diffusion imaging has the potential to yield quantitative information related to tissue microstructure[1], including hypercellularity[2] and tumor invasiveness into white matter[3]. Current investigation into quantitative MRI suggests apparent diffusion coefficient (ADC) values may be useful in classifying tumors[4]. However, systematic variation and bias may hinder widespread application of quantitative MRI (qMRI) and qMR-diffusion. Sources of systematic bias include protocol, gradient performance, and hardware (e.g., signal-to-noise (SNR) from coil choice), which in theory can be minimized, given a suitable test object for calibration purposes. In addition, daily quality assurance could be performed with such an object in order to maintain the necessary performance for qMRI. Therefore, the need for a clinically relevant test object that can reproducibly measure diffusion imaging metrics is paramount. The goal of this initial study is to characterize and apply thermal and SNR corrections to diffusion tensor images (DTI) of a phantom via regression, to facilitate the future study of intrinsic systemic biases present in clinical protocols.

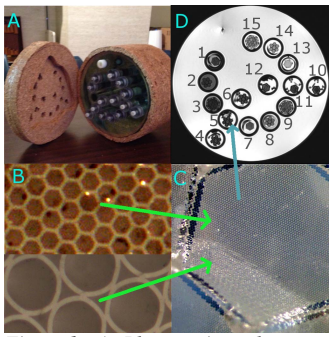

Figure 1—A: Phantom in cork enclosure. B: close-up of hexagonal (top) and close-packed (bottom) capillary arrays. C: Individual capillary array. D: T2 image of phantom, showing different compartments with multiple arrays.

Methods:
Phantom Construction: The Diffusive Quantitative Imaging Phantom (DQIP) consists of a large cylindrical central compartment (~1.54L) and fifteen smaller cylindrical compartments (~9.5-13mL in volume), shown in Figure 1. Each smaller compartment contains arrays of glass capillaries of varying inner diameters: 20 µm, 40 µm, and 200 µm i.d. capillaries within three sets of compartments, for examining the effect of SNR on FA and ADC (compartments 1-3@SNR #1; 7-9@SNR #2; 13-15@SNR #3); and 23 µm and 35 µm i.d. capillaries within three compartments each (4-6, and 10-12), for examining the dependence of FA and ADC on radial position. The capillaries were of two varieties: tubes with a hexagonal cross section, and close-packed tubes with small compartments surrounding the tubes. All compartments were filled with deionized water doped with $CuSO_4$ (14.7 mM) and NaCl (74 mM). Compartments #1-3 and #7-9 were doped with heavy water (~ 2:1 D_2O:H_2O and ~3:7 D_2O:H_2O, respectively) to reduce SNR.

To constrain temperature, two passive precautions were undertaken. First, a cork enclosure was constructed for the phantom to increase thermal stability during scanning. Temperature stability was measured to be 0.1 °C/hr for each °C difference between room and phantom with the cork, compared with 0.24°C/hr•°C without the cork. Second, the phantom was stored between scans in a temperature-controlled Peltier incubator, maintained at 21.8 °C to match the mean scan room temperature. Temperature was monitored during each scanning session using an Oakton Thermometer (Oakton Instruments, Vernon Hills, IL) and a thermistor mounted within the phantom. Temperatures of the phantom were measured at the start and end of each imaging series. Temperature change during the hour-long MR exam was consistent with 0.1 °C stability.

MR Imaging: Images were acquired using a GE Excite HDx 3.0T MRI scanner (GE Medical Systems, Milwaukee, WI) and an eight-channel phased-array coil. Initial data was acquired on five different days, using a protocol with six diffusion-imaging sequences. For this study, data from a clinical DTI sequence was used with the following parameters: TE/TR: 88.5/8000 msec; Matrix: 128 x 128; FOV: 25.6 cm, Slice Thk: 3.00 mm; no gap; 25 directions; b=1000 mm²/sec; 28 slices). Nine DTI series were also acquired periodically to measure the thermal dependence of diffusion during an additional 7-hr scan session, for which the phantom was set initially to 37.7°C via the incubator and allowed to relax.

Data Processing: A weighted-least-squares fitting routine was used to calculate trace ADC (tADC) and fractional anisotropy (FA) maps, using in-house software written in Matlab (Mathworks, Natick, MA). Masks were generated for each compartment. SNR and temperature were measured and regressed out of the data collected on different days for each compartment. Thermal and SNR trends were fit iteratively in alternation with each other, to avoid the dominance of low SNR over thermal effects during multiple regression. Linear dependences of FA and tADC were assumed in proportion to temperature, and inversely proportional to SNR.

Results:
Figure 2 shows representative fits of FA and tADC dependence on temperature and SNR for four different compartments, where the effects of one variable were removed at each step before fitting the dependence of the other. SNR effects were most predominant for low FA value compartments (shown by the change in temperature dependence before and after SNR regression for blue data points). After regression, the ranges of temperature dependence were $\Delta(FA/^{o}C) = ((-2.0) - 8.1)\ e^{-3}/^{o}C$ and $\Delta(tADC/^{o}C) = (2.0 - 5.6)e^{-5}$ mm²/sec °C. SNR dependence ranges were $\Delta(FA/SNR^{-1}) = 0.4 - 4.3$, and $\Delta(tADC/SNR^{-1}) = ((-7.9) - (-1.0))e^{-3}$ mm²/sec.

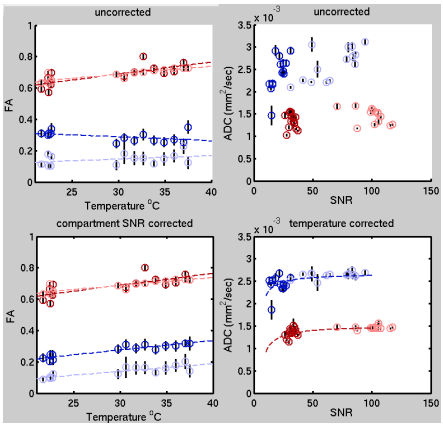

Figure 2: Representative FA and tADC data, before corrections for temperature and SNR, for four compartments (red/pink =20 µm i.d.capillaries; blue/cyan=200 µm i.d.), with regression fits.

Figure 3 shows the range of FA and tADC values for each compartment as well as the standard deviation over five measurements after corrections. Even after regression (i.e., setting SNR and temperature within each compartment self-consistent over time), significant FA differences between compartments remained because of gross SNR dependences, as expected. In particular, the 40 µm (in green), and 200 µm (in blue) i.d. capillaries show a significant FA deviation in both low (compartments 2,3) and medium (compartments 8,9) SNR values compared with high SNR (compartments 14,15) values, using a student t-test.

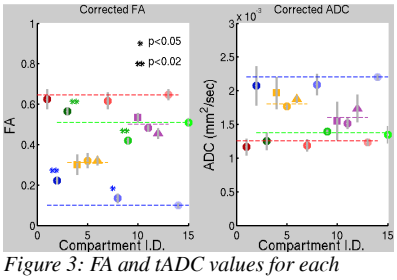

Figure 3: FA and tADC values for each compartment, corrected for SNR and temperature. Colors indicate similar capillary i.d, while symbols indicate radial position.

Discussion:
Diffusion quantitative imaging may provide further insight into clinical conditions but inherent systematic biases exist with image acquisition. The present study describes a new phantom, DQIP, for reproducible measurement of diffusion imaging metrics in a clinical setting. The phantom design allows for precise measurement of FA, tADC, with their SNR and temperature dependences. FA measurements were significantly dependent upon SNR, particularly in compartments with lower FA values.

Conclusion: Standardization of diffusion imaging metrics in quantitative MRI is essential to ensure accurate and reproducible results taking into account scanner and protocol related variability. The DQIP phantom was developed to aid in analyzing inherent systematic biases for MR-based diffusion imaging.

References
1) Beaulieu C, 2002, NMR Biomed, 435-55. 2) Guo Y et al., 2002, JMRI, 172-8. 3) Jellison BJ et al, 2004, AJNR, 356-69. 4) Khayal IS, et al., 2009, NMR Biomed, 449-55.