A Simple Isotropic Phantom for Diffusional Kurtosis Imaging

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INTRODUCTION: Diffusional kurtosis imaging (DKI) is a minimal extension of diffusion tensor imaging (DTI) that, in addition to the standard DTI metrics (e.g., mean diffusivity and fractional anisotropy), provides estimates for the kurtosis of the diffusion displacement probability distribution function and related measures of diffusional non-Gaussianity[1-3]. Recent studies indicate that DKI may be useful for investigating a variety of neuropathologies, including brain cancer,[4] mild traumatic brain injury,[5] and attention deficit hyperactivity disorder.[6] To minimize systematic errors for multicenter and longitudinal applications of DKI, it is vital to establish a calibration material with known diffusion coefficient and (nonzero) diffusional kurtosis that are similar to those observed *in vivo* for brain. We show here that heavy dairy cream, which has been previously proposed as a standard for evaluating biexponential fitting of the T_2-weighted[7] and diffusion-weighted[8] signal decay, is also a suitable and convenient phantom for testing clinical DKI protocols.

METHODS: Aliquots (350 ml) of heavy cream (~36% w/w fat) were submerged in a hot water bath at 80˚C. After reaching 60˚C, they were left in the bath for 10 minutes and then allowed to cool to room temperature (18.5˚C). All phantoms were imaged the following day on a 3T wide-bore Siemens Verio system with a 12-channel head coil using a standard DKI sequence[1,9] with TR = 3 s and TE = 105 ms and without fat suppression or parallel imaging. For each scan, a coronal slice was taken with an in-plane resolution of 2.5 × 2.5 mm^2, while the slice thickness varied from 1 mm to 10 mm to evaluate the effect of noise. Additional $b = 0$ images were acquired for TE = 85, 95, 120 and 150 ms.

DTI and DKI parametric maps were derived using in-house software[9], and the additional $b = 0$ images for increasing TE were used to derive T_2-maps. The difference in resonance frequency results in spatial misregistration between fat and water molecules along the phase-encoding (left-right) direction (Fig. 1), allowing regions of interest (ROIs) to be drawn of only water, only fat and both fat and water (i.e., cream). The apparent water fraction f was derived from the $b = 0$ images as $f = S_{water} / (S_{fat} + S_{water})$, where S_{water} and S_{fat} are the mean signals in the water-only and fat-only ROIs. Similarly, the mean values and standard deviations of the mean diffusivity (MD) and mean kurtosis (MK) were derived for water (D_{water}, K_{water}), fat (D_{fat}, K_{fat}), and cream (D_{cream}, K_{cream}).

The diffusion signal S in the cream was modeled by two non-exchanging diffusion components. Assuming $D_{fat} \approx 0$, the total diffusion coefficient $D_{2\text{comp}}$ and kurtosis $K_{2\text{comp}}$ can then be predicted as a function of D_{water}, K_{water} and f by:

$$D_{2comp} = fD_{water}; \quad K_{2comp} = \frac{1}{f}\left[3(1-f) + K_{water}\right].$$

To test of our DKI protocol, we compared $D_{2\text{comp}}$, $K_{2\text{comp}}$ to the directly measured D_{cream}, K_{cream} values. As the latter values are obtained from a standard DKI fit[1], a bias may be present because of neglecting the higher order cumulants of the diffusion signal. The theory described in Ref. 1 was used to adjust D_{2comp} and K_{2comp} for this bias, resulting in D_{fit} and K_{fit}.

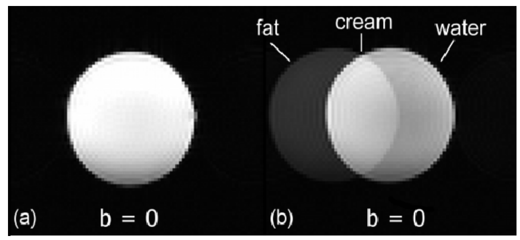

Figure 1: EPI-image ($b = 0$, TE = 105 ms) of the cream phantom (a) before and (b) after heating.

RESULTS: The effect of the heat treatment of the cream is illustrated in Fig. 1. Before heating, only the water image is visible because of a short T_2 for the fat protons; after heating, both the water and fat images are apparent, with fitted T_2-relaxation times of 57 ± 4 ms and 47 ± 2 ms for water and fat, respectively. Figure 2 shows the corresponding MD and MK maps. Mean values and standard deviations for MD and MK are: $D_{fat} = 0.01 \pm 0.02$ μm^2/ms, $D_{cream} = 1.08 \pm 0.02$ μm^2/ms, $D_{water} = 1.35 \pm 0.02$ μm^2/ms, $K_{cream} = 1.18 \pm 0.04$, and $K_{water} = 0.15 \pm 0.07$. The phantoms were reproducible within 3% for both the MD and MK. The measured and predicted values for the MD and MK in cream and water are plotted in Fig. 3 as a function of the slice thickness. D_{cream} and K_{cream} are predicted by D_{2comp} and K_{2comp} to within 10%, or when compensating for the truncation bias by using D_{fit} and K_{fit}, to within 5%.

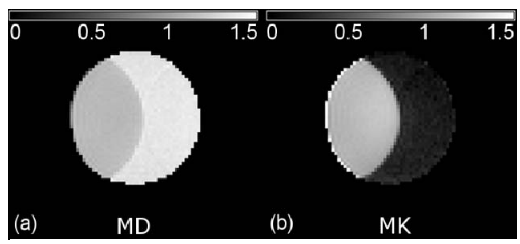

Figure 2: Parametric maps of the mean diffusion (MD) coefficient (a), and the mean kurtosis (MK) (b). The scale bar for the MD is in units of μm^2/ms.

DISCUSSION: The prescribed heat treatment of the cream causes a significant increase in T_2 of the fat, which enables testing clinical DKI protocols having TE ~ 100 ms. The MR-visible fat and water protons of cream give rise to a diffusion coefficient of about 1.1 μm^2/ms and a diffusional kurtosis of 1.2, similar to the DKI parameter values observed *in vivo* for human brain[1-3]. A feature of this phantom is that the fat-water shift is exploited to obtain measurements in each compartment separately, as well as for the cream. The data plotted in Fig. 3 clearly demonstrate good agreement between the measured and predicted diffusivity and kurtosis values, when thicker slices are used, and thus they provide a consistency check for the DKI protocol. For thinner slices, the predicted values are overestimated due to a poor signal-to-noise ratio for the water images with high b-values. In summary, heat-treated dairy cream provides a practical and inexpensive phantom for the testing of DKI protocols intended for neuroimaging applications.

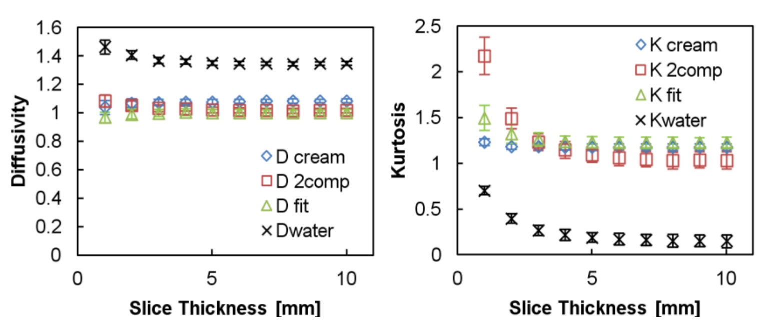

Figure 3: (a) The diffusion coefficient in the cream (D_{cream}, $D_{2\text{comp}}$, D_{fit}) and water (D_{water}), and (b) the diffusional kurtosis in the cream (K_{cream}, $K_{2\text{comp}}$, K_{fit}) and water (K_{water}), as a function of the slice thickness.

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