High-resolution diffusion tensor imaging of the human brain

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Introduction

Diffusion tensor imaging provides the capability to elucidate tissue microstructure and microstructural changes in disease, and to provide quantitative imaging parameters indicative of changes in physiologic state for clinical assessment and monitoring. While this MRI modality has been demonstrated *in vivo* using conventional spin-echo diffusion-weighted sequences, long acquisition times and high sensitivity to motion artifacts have precluded its clinical implementation. Although single-shot diffusion weighted images have overcome these difficulties, their low resolution and phase-encoding artifacts have precluded widespread use for radiological assessment. Here we demonstrate the clinical feasibility of high-quality, high-resolution diffusion tensor imaging in human brain.

Materials and Methods

Normal subjects, between 20 to 55 years old, were scanned in a 4-Tesla whole-body imaging system, equipped with 15 mT/m A-NMR gradients. Images were acquired using a recently developed interleaved EPI diffusion-weighted STEAM sequence with navigator echo corrections of motion artifacts. A description of this sequence and the image reconstruction algorithm is given elsewhere (1). Imaging parameters were: TR=4s (cardiac gated to one slice per heart beat, 4 slices), TE=50ms, TM=200ms, FOV=240mm, res=128x128, slice thickness=5mm, diffusion gradient duration= 10ms, diffusion time= 235ms.

We obtained 25 axial, diffusion-weighted images of human brain in 30 minutes. Diffusion gradients were applied in 6 noncollinear directions in which two gradients were applied simultaneously in order to augment the attenuation of the measured echoes to diffusion. After images were reconstructed, the b matrix was calculated for each image by taking into account the attenuation and coupling due to the imaging gradients (2) as well as diffusion. The six independent elements of the diffusion tensor, $\underline{D}$ and the T_2-weighted amplitude, A(0), were estimated in each voxel (3) Using $\underline{D}$, we calculated several invariant scalar quantities derived from the diffusion tensor (3) including, the principal diffusivities (i.e., the diffusivities in the tissue's own coordinate frame of reference: λ_1, λ_2, and λ_3), the sum of the diagonal elements of the diffusion tensor, Trace($\underline{D}$), and invariant anisotropy indices such as the ratio of the principal diffusivities, λ_1 / λ_3.

Results and Discussion

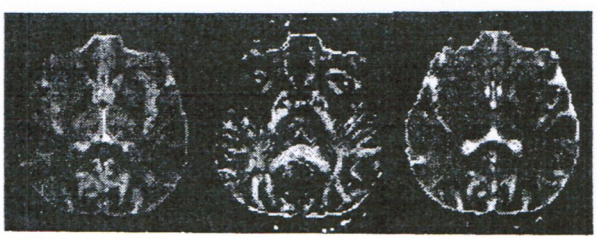
Figure 1 shows axial images at the level of the basal ganglia. Figure 1a shows a T_2-weighted amplitude image A(0); Figure 1b shows an anisotropy index image; and Figure 1c shows a Trace($\underline{D}$) image. A(0) is estimated at the same time as the elements of the diffusion tensor. It has similar contrast to an image obtained with the same timing parameters but without diffusion sensitization, however, it is less noisy. It represents the part of the measured signal attenuation that cannot be explained by diffusion. As a result, A(0) provides complementary information to that contained in $\underline{D}$. The anisotropy index image is a ratio of the diffusivities of water parallel and perpendicular to the nerve fiber tracts, $D_{\parallel} / D_{\perp}$, *independent of orientation within the tissue.* Bright voxels indicate high diffusion anisotropy, and correspond to regions of white matter fibers; dark voxels indicate low anisotropy, which is observed in the ventricles and regions containing grey matter. The brightest voxels contain the most highly ordered white matter fiber tracts in which λ_1/λ_3 can exceed 10. This is approximately three times larger than what is usually reported, but is consistent with our findings in monkey brain using high-resolution diffusion tensor imaging (4). This disparity is explained in part because partial volume artifacts in lower-resolution images depress λ_1/λ_3 significantly, and approximating it by using ratios of ADCs in mutually perpendicular directions systematically underestimates it. Moreover, $\lambda_1 \approx 1.5 \times 10^{-3}$ mm^2/sec and $\lambda_3 \approx 0.15 \times 10^{-3}$ mm^2/sec in compact white matter, indicating that even parallel to the fiber-tract direction, water diffusion is lower than observed in aqueous solution.

Finally, the image of Trace($\underline{D}$) highlights regional differences in mean diffusivity such as within ventricles in which diffusion is free (Trace($\underline{D}$) $\approx 8.2 \times 10^{-3}$ mm^2/sec) and within parenchyma in which diffusion is reduced (Trace($\underline{D}$) $\approx 1.9 - 2.4 \times 10^{-3}$ mm^2/sec).

Concluding Remarks

We have successfully demonstrated high-resolution, clinical *diffusion tensor images*(DTI) acquired in 30 minutes.

DTI provides *objective* and *quantitative* information about intravoxel water mobility which should improve the clinical assessment of physiological state and of tissue microstructure.



(a) (b) (c)

Fig 1. a) T_2-weighted amplitude image, A(0), b) anisotropy index image, λ_1 / λ_3 c) Trace($\underline{D}$) image (axial section).

References

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