Diffusion Tensor Imaging at 3T with Strongly Reduced Geometric and Intensity Distortions

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Introduction

Images acquired using echo planar imaging (EPI) are susceptible to local field inhomogeneities, induced for example by local magnetic susceptibility variations at tissue-air or tissue-bone interfaces, which distort the image in the phase encode direction[1]. Generally, images appear stretched or compressed, and signal intensity is affected as well. These artefacts diminish diffusion tensor imaging[2] (DTI) in the human brain, where EPI is still the method of choice. This problem is even more severe in high field MRI scanners. We present a spin echo EPI DTI sequence based on the reversed gradient method[3,4,5,6] which overcomes these limitations. It is shown that effective resolution is increased in parts of the brain that normally appear compressed by susceptibility artefacts, and that fiber tracking yields more accurate results as well, for the price of doubled scan time. This is demonstrated in particular for the cerebellum.

Methods

Images were acquired on a GE 3T scanner with 50 mT/m gradients using a 2D spin echo EPI sequence with TE/TR = 0.1/10 s. 30 slices of 5 mm thickness and a resolution of 128 x 128 were acquired axially in 1 NEX. The DTI sequence contained 26 gradient directions (*b*-values from 815 to 1153 s/mm^2) and 6 acquisitions without diffusion weighting. The FOV was chosen as 30 cm to ensure imaging of all geometric distortions. The overall scan time was twice 5 min 24 s (for each of the two gradient directions in the reversed gradient method). Diffusion tensors were computed using singular value decomposition with account taken of the differing SNR at each *b*-value. In the reversed gradient method two images with the phase encode gradient in opposite direction are acquired. In the first image, for each point on the frequency encode axis, x_0, magnetic field induced distortions show up mainly in the phase encode direction (along y), and in the second image along $-y$. The displacement is $\Delta y(x_0) = \Delta B(y(x_0))/|G_y|$, where $\Delta B(y(x_0))$ is the magnetic field inhomogeneity and G_y is the gradient in y direction. For each x_0, this procedure yields one image with intensity $I_-(y_-)$ with voxels at position $y_- = y-\Delta y$, and another image with intensity $I_+(y_+)$ with voxels at position $y_+ = y+\Delta y$. These displacements were corrected by the method of Chang and Fitzpatrick[7]: The images were first merged by $y = (y_+ + y_-)/2$ and then the intensity distortions (arising as a consequence of spatial distortions) were corrected by $I = 2I_+I_-/(I_+ + I_-)$, for each x_0. Fiber tracking in the cerebellum was performed by a continuous tracking algorithm[8,9] which stopped fiber continuation for a relative anisotropy value < 0.1. All post processing was done by software written in C and IDL (Research Systems, Inc.).

Results

We found that the distortions induced by local susceptibility inhomogeneity affect fractional anisotropy (FA) values which are significantly increased in compressed parts of the image. The effects on geometry are also severe: We could identify regions in the brain that were compressed so much that particular structures were lost. This is demonstrated in Fig. 1 which shows an axial FA map for only one gradient direction (a) and the corrected image based on both gradient directions (b). Fig. 1c shows an anatomical image for comparison. The middle cerebellar peduncle (mcp) is only visible in the corrected image. Therefore, one can say that the effective image resolution has increased using the reversed gradient method in DTI. The result on fiber tracking is shown in Fig. 1d,e: right-left fibers for both the mcp and the pontine crossing tract (pct) are only visible in the reversed gradients image, and the considerable fiber distortion in Fig. 1d has been corrected completely.

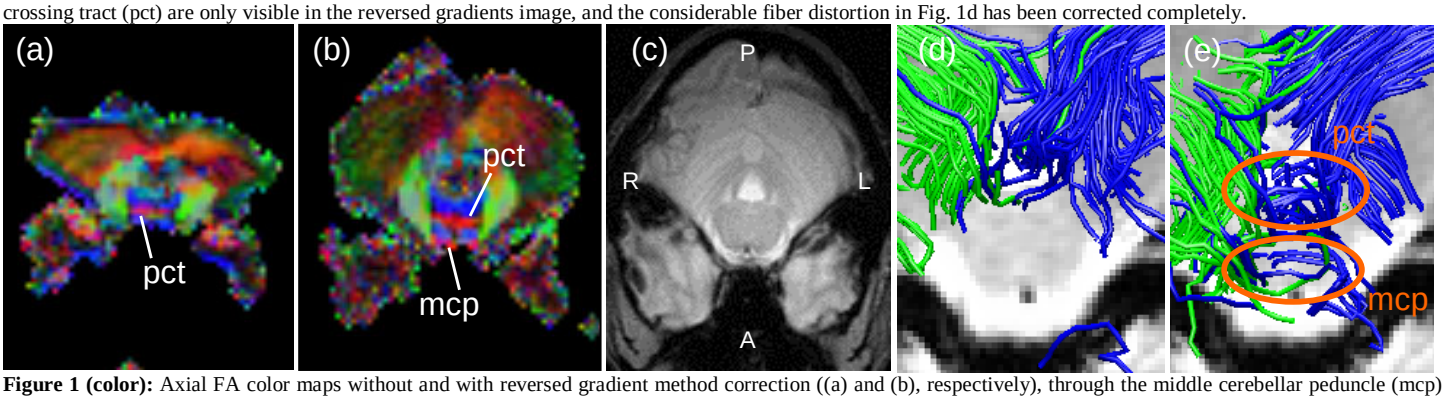

Figure 1 (color): Axial FA color maps without and with reversed gradient method correction ((a) and (b), respectively), through the middle cerebellar peduncle (mcp) and pontine crossing tract (pct), both appearing in red. (c) is a gradient echo anatomical image for reference. In (a) only the pct is visible. This is also reflected in fiber tracking without and with correction ((d) and (e), respectively, overlaid to a T2w anatomical slice). In (d) tracts appear shifted and the pct is missing. Colors in FA maps denote predominant diffusion direction: Green, posterior-anterior, blue, superior-inferior, red, left-right. Colors in tractography images correspond to different seed point locations.

Discussion

We proposed a combination of echo planar diffusion tensor imaging and reversed gradients to obtain images with strongly reduced geometric and intensity distortions at 3T. Reversed gradients were applied to human brain DTI without using parallel imaging or multiple acquisitions (as opposed, e.g., to the more accurate results of Wakana et al.[10]). In-plane distortions due to the echo planar sampling scheme could be reduced almost completely within the limits of the method[5], as well as increased anisotropy in compressed parts of the image. The latter point may be of importance for quantitative clinical applications since susceptibility artefacts depend on many parameters and are hard to reproduce exactly. A certain drawback is the doubled scan time. Future work will focus on decreasing scan time by obtaining reference images for only a small number of diffusion directions. It remains to be seen if image correction is still possible in a sufficient approximation.

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