Available online at www.sciencedirect.com
ScienceDirect
Magnetic Resonance Imaging 24 (2006) 1369–1376
MAGNETIC RESONANCE IMAGING

How does distortion correction correlate with anisotropic indices? A diffusion tensor imaging study

Dae-Jin Kim[a], Hae-Jeong Park[b], Kyung-Whun Kang[c], Yong-Wook Shin[c], Jae-Jin Kim[d], Won-Jin Moon[e], Eun-Chul Chung[e], In Young Kim[a,*], Jun Soo Kwon[c], Sun I. Kim[a]

[a]*Department of Biomedical Engineering, Hanyang University, Seoul 133-605, South Korea*
[b]*Department of Diagnostic Radiology, College of Medicine, Yonsei University, Seoul, South Korea*
[c]*Department of Psychiatry, Seoul National University, Seoul, South Korea*
[d]*Department of Psychiatry, Severance Mental Health Hospital, College of Medicine, Yonsei University, Seoul, South Korea*
[e]*Department of Radiology, Kangbuk Samsung Hospital, Sungkyunkwan University School of Medicine, Seoul, South Korea*

Received 16 November 2005; accepted 29 July 2006

Abstract

Purpose: The purpose of this study was to determine a suitable registration algorithm for diffusion tensor imaging (DTI) using conventional preprocessing tools [statistical parametric mapping (SPM) and automated image registration (AIR)] and to investigate how anisotropic indices for clinical assessments are affected by these distortion corrections.
Materials and Methods: Brain DTI data from 15 normal healthy volunteers were used to evaluate four spatial registration schemes within subjects to correct image distortions: noncorrection, SPM-based affine registration, AIR-based affine registration and AIR-based nonlinear polynomial warping. The performance of each distortion correction was assessed using: (a) quantitative parameters: tensor-fitting error (E_f), mean dispersion index (MDI), mean fractional anisotropy (MFA) and mean variance (MV) within 11 regions of interest (ROI) defined from homogeneous fiber bundles; and (b) fiber tractography through the uncinate fasciculus and the corpus callosum. Fractional anisotropy (FA) and mean diffusivity (MD) were calculated to demonstrate the effects of distortion correction. Repeated-measures analysis of variance was used to investigate differences among the four registration paradigms.
Results: AIR-based nonlinear registration showed the best performance for reducing image distortions with respect to smaller E_f (P<.02), MDI (P<.01) and MV (P<.01) with larger MFA (P<.01). FA was decreased to correct distortions (P<.0001) whether the applied registration was linear or nonlinear and was lowest after nonlinear correction (P<.001). No significant differences were found in MD.
Conclusion: In conventional DTI processing, anisotropic indices of FA can be misestimated by noncorrection or inappropriate distortion correction, which leads to an erroneous increase in FA. AIR-based nonlinear distortion correction would be required for a more accurate measurement of this diffusion parameter.

Keywords: Diffusion tensor imaging; Distortion correction; Image registration; Evaluation

1. Introduction

Diffusion tensor imaging (DTI) allows in vivo investigation of molecular diffusion within biological tissues, such as skeletal and cardiac muscles, spinal cord and brain white matter (WM). The recent development of diffusion imaging techniques [1,2] has enabled DTI to be used in the diagnosis and assessment of various neurological disorders, such as stroke, schizophrenia, multiple sclerosis, brain tumors and developments [3–7]. A number of studies that have assessed the characteristics of brain tissue have used two types of rotationally invariant scalar measures derived from diffusion tensor, mean diffusivity (MD) [1,8] and anisotropic index, such as fractional anisotropy (FA) [9]. In clinical DTI applications, it is important to determine these diffusion measures as accurately as possible. Accurate calculation of diffusion tensor is essential for tracing the direction of principal diffusivity with fiber bundle tracking or fiber tractography [10–14].

Diffusion measures in DTI suffer from artifacts caused by subject motion, physiological pulsation, eddy currents,

* Corresponding author. Tel.: +82 2 2291 1713; fax: +82 2 2296 5943.
E-mail address: iykim@hanyang.ac.kr (I.Y. Kim).

0730-725X/$ – see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.mri.2006.07.014

magnetic susceptibility effects and intrinsic image noise. Various methods have been suggested to reduce these artifacts [15–17]. Eddy currents produced by extreme gradients in rapidly switching magnetic fields, especially in echo-planar imaging (EPI), which is extensively used in DTI applications, can result in significant image distortions in diffusion-weighted images (DWIs). Hardware [18] and pulse sequence [19–23] correction methods have been proposed as ways of reducing these undesirable distortions. Although these methods have some advantages in reducing image distortions for DWI acquisition, they do not completely remove distortions caused by all artifact sources. Postprocessing approaches, such as coregistering DWIs to a reference image (e.g., a non-DWI), have been widely used to reduce image distortion [24–26] because they do not affect the acquisition procedure itself and can be used for analysis without prior calculation of diffusion measures.

Conventional image analysis tools, such as statistical parametric mapping (SPM; Wellcome Department of Cognitive Neurology, Institute of Neurology, University College London, London, UK) or an automated image registration (AIR) program [27,28], have been widely used in clinical applications. However, the performance of these tools has not yet been quantified in the DTI area. Moreover, it is not known how diffusion indices are affected by distortion correction using these conventional tools.

Because image distortions may introduce measurement errors in estimating diffusion indices of FA and MD, which are critical for assessing the properties of WM, the accuracy of these diffusion indices is important for both clinical and scientific investigations. In this study, we systematically evaluated the performance of conventional registration methods for correcting image distortion including: SPM-based affine, AIR-based affine and AIR-based nonlinear transformation. We focused on how significantly these distortion corrections affected the diffusion indices of FA and MD and determined which method was suitable for the conventional preprocessing of DTI. For this study, we used regions of interest (ROI) analysis with homogeneous fiber bundles, which allows quantitative measurements of the properties of WM and fiber tractography with visual analysis. We then used several quantitative parameters to compare the results of distortion correction: tensor-fitting error (E_f), mean dispersion index (MDI), mean fractional anisotropy (MFA) and mean variance (MV) (for details, see Section 2.5).

2. Materials and methods

2.1. Subjects

DTIs were acquired from the brains of 15 normal healthy subjects (25–34 years; average: 29.1±2.8 years) with no brain morphology abnormalities, neurological illness, head trauma, loss of consciousness or psychiatric disorders. After carefully describing the scope of the study, we obtained written informed consent from all subjects. The local ethics committee at our institution approved the scanning protocol. This study was carried out under guidelines for the use of human subjects established by the institutional review board.

2.2. DTI acquisition

All scans were acquired using a Philips 1.5-T scanner (Philips Intera; Philips Medical System, Best, The Netherlands), which was equipped with shielded magnetic field gradients of 30 mT/m. A SENSivity Encoding (SENSE) head coil was used for radiofrequency transmission and reception of nuclear magnetic resonance signals [29]. Head motion was minimized with restraining foam pads provided by the manufacturer. Sagittal T_1-weighted images were acquired with slices clearly showing the anterior commissure (AC) and the posterior commissure (PC). Diffusion-encoded images parallel to the AC–PC line were then obtained using single-shot echo-planar acquisition with the following parameters: acquisition matrix=112×112, reconstructed to 128×128; voxel=1.96×1.96×2 mm^3, reconstructed to 1.7×1.7×2 mm^3; axial slice=70; field of view=220 mm; T_R/T_E=13,063.39/70 ms; flip angle=90°; slice gap=0 mm; average per slice=2; b factor=600 s mm^{-2}; SENSE factor=2; noncardiac gating. The baseline image had no diffusion weighting, and DWIs were acquired from 32 different directions, with the baseline image having no diffusion weighting. The imaging time for acquiring one DTI data set was approximately 14 min.

2.3. Data processing and distortion correction

Raw data from the scanner were converted into the ANALYZE 6.0 (Mayo Foundation, Rochester, MN, USA) readable form using in-house software DoDTI (http://neuroimage.yonsei.ac.kr/dodti/). To determine brain tissue in each volume, nonbrain areas on the DWIs were removed semiautomatically using an object extractor module. Correction of image distortion was performed by registering all DWIs to the non-DWI of each brain using a modified SPM algorithm to execute three-dimensional registration with parameter adjustments and AIR (version 5.2.5), respectively. We evaluated the performance of three spatial registration methods: (a) SPM-based affine registration maximizing mutual information (MI) [30] with default parameters; (b) AIR-based affine registration minimizing the standard deviation (S.D.) of ratio images between DWIs and the reference image; and (c) AIR-based second-order nonlinear 30-parameter polynomial transformation model. After generating the diffusion tensor matrix from a series of 32 DWIs, three eigenvalues and eigenvectors were calculated by matrix diagonalization [1,9]. FA and MD maps were generated from the eigenvalues of the diffusion tensor [10,31].

2.4. ROI

Eleven ROI were obtained from color-encoded DTI maps of the principal eigenvector using DoDTI (Fig. 1). Each ROI