Multi-tensor Tractography of the Motor Pathway at 3T: A Volunteer Study

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Conventional single-tensor tractography cannot depict the entire motor tract of the corticospinal tract because of fiber-crossing and other factors. Using a 3-tesla magnetic resonance (MR) unit, we compared single- and multi-tensor methods for the tract ratio of the 5 major components of the motor pathway, the lower extremity, trunk, hand, face, and tongue, in 5 healthy volunteers. Multi-tensor tractography is better than single-tensor tractography at 3T in depicting more fibers of non-trunk areas from the primary motor cortex.

Keywords: corticospinal tract, DTI, tractography, 3T

Introduction

Fiber tractography based on diffusion tensor imaging (DTI) is widely used to identify the motor fibers of the corticospinal tract,1-4 but it has some limitations. Conventional single-tensor tractography cannot differentiate fiber-kissing and oblique fiber-crossing or -branching because it over-simplifies the information within a voxel to represent a fiber tract in a single direction.1,5-8 Thus, single-tensor tractography is limited to only part of the entire tract and is not ideal for correctly estimating the location of brain fibers.9-11 Because underestimation of motor fibers in areas of fiber-crossing can mislead the surgeon and result in serious damage to the pyramidal tract during surgery,12 methods have been proposed to depict all fibers.13-16 Among these, high angular resolution diffusion imaging (HARDI) may be valuable in a clinical setting. DTI of the brain yields a higher signal-to-noise ratio (SNR) at 3.0 than 1.5 tesla.17 Higher field strength magnetic resonance (MR) scanners also offer significantly better visualization of the fiber tracts.18-20 However, to our knowledge, the feasibility of HARDI-based multi-tensor tractography for the corticospinal tract at 3T has not been investigated. In 5 healthy volunteers, we examined our hypothesis that the HARDI-based multi-tensor technique can visualize fibers of the corticospinal tract from wider areas of the motor cortex with a short acquisition time at 3T.

Materials and Methods

Our institutional review board approved the study, and we obtained informed consent from all 5 healthy male volunteers (aged 23 to 44 years; mean, 31 years) before MR examinations.

Diffusion tensor imaging technique

All images were obtained with a 3.0T clinical MR unit (Achieva 3.0T; Philips Medical Systems, Best, The Netherlands). We used single-shot echo-planar imaging for DTI with repetition time (TR), 10172 ms; excitation time (TE), 93 ms; diffusion-sensitizing gradient in 32 orientations; and b-value, 1000 s/mm². We applied a parallel imaging technique at a reduction factor of 2.5 with parameters: 128 × 128 matrix; field of vision (FOV), 230 × 230 mm; and one acquisition. We acquired a total of 60 sections of 2-mm thickness each without intersection gaps. Voxel size was 1.8 × 1.8 × 2.0 mm, and acquisition time was 7 min 12 s.

Data processing for fiber tracking

We used both conventional single- and multi-tensor methods for data post-processing. We transferred DTI data to an off-line workstation for registration and analysis and analyzed images using PRIDE software (Philips Medical Systems, Best, The Netherlands). To remove distortion and possible head motion over various sections and scans, we registered the DTI data with respect to the b = 0
measurement using the method of Netsch and van Muiswinkel.21

**Single- and multi-tensor modeling**

The details of single- and multi-tensor modeling have been described elsewhere.11 In single-tensor tractography, 32 apparent diffusion coefficients (ADCs) calculated for each voxel were used to fit a 3-dimensional (3D) ellipsoid or tensor model. The direction of the main tensor axis (DTA) was used for fiber tracking.

For multi-tensor analysis, we fit the data of the 32 directional ADCs to a 2-tensor model that was described by Frank.22 The 3 diffusivities ($\lambda_1$, $\lambda_2$, and $\lambda_3$) of each tensor were restricted to a range of $\lambda_i$ minimum and $\lambda_i$ maximum. For our calculations, we set these values to 1.2/1.8 ($10^{-3}$ mm$^2$/s) for $\lambda_1$; 0.2/0.7 ($10^{-3}$ mm$^2$/s) for $\lambda_2$; and 0.2/0.7 for $\lambda_3$ ($10^{-3}$ mm$^2$/s). Because they are close to the diffusivities found in highly oriented white matter, such as the spinal cord and corpus callosum, in our model, we assumed that a voxel with crossing fibers consists of 2 individual fibers with highly oriented patterns of diffusion.

**Fiber-tracking methods**

In single-tensor tractography, we performed tracking by extending the DTA of each voxel and using a stream-lined algorithm with Runge-Kutta interpolation of the fiber direction.5 Based on the method of Yamada and associates,11 we performed tracking only when the following 3 criteria were met: the signal intensity on the b=0 image exceeded 200; the FA value exceeded 0.1 to 0.3; and the angle by which the tract changed from one voxel to the next did not exceed 27°.

In multi-tensor tractography, one tract may be split into two based on the DTA of each voxel after the tract arrives at a voxel consisting of 2 tensors. As in the method of Yamada,11 branching was allowed only when 2 criteria were met, that is, the volume fraction of the respective tensor was larger than 5%, and the angle $\pi$ (the difference between the 2 DTAs) was larger than 12°. If either of the above criteria was not met, the voxel was considered to match a single-fiber model, and tracking was carried out as in single-tensor tractography.

**Placement of regions of interest (ROI)**

According to Yamada’s method,11 one neuroradiologist placed ROIs on each hemisphere. To trace the motor pathways of a single hemisphere, 5 ROIs were placed over the primary motor cortex (Fig. 1a); a single ROI was placed at the ventral part of the pons (Fig. 1b). We identified the primary motor cortex using established neuroradiologic methods.23–25 Based on Penfield’s motor homunculus, the 5 cortical ROIs were placed over the tongue, face, hand, trunk, and lower extremity (LE). We used the transaxial plane to place ROIs in the hand/trunk areas and the sagittal plane for the face/tongue and LE areas. The size and shape of the ROIs were identical for single- and multi-tensor tractography. The hand ROI was placed by identifying the “hand knob” of the primary motor cortex;24 the trunk ROI was placed medial to the hand ROI. The ROI of the LE was located medial to the trunk ROI on the sagittal plane. Similarly, the face and tongue ROIs were placed lateral to the hand ROI on the sagittal plane. The location of the ROI at the pons was based on the color vector map. We first identified a pair of regions containing fibers oriented craniocaudally coursing through the pons, then placed the ROI over the ventral part of these areas.

**Image analysis and statistics**

We calculated a total of 5 specific tracts per person in about 10 hours. We recorded the number of fibers in each of the 5 specific areas (LE, trunk, hand, face, and tongue) to calculate the “tract ratio” for each hemisphere, i.e., the relative number of fibers per hemisphere derived from the formula: tract ratio = number of fibers in one tract bundle/total number of all fibers depicted in a single hemisphere.

To investigate the effect of the 2 tractography methods on fiber-bundle visualization, we compared the tract ratios of non-trunk areas (LE, hand, face, and tongue) on single- and multi-tensor tractographs. We used paired Student t-test to determine the statistical significance of differences, with $P<0.05$ considered significant.

**Results**

Tractography was successful in all 10 hemispheres of the 5 volunteers. Figures 2 and 3 show the fiber ratio for each of the 10 hemispheres.

With single-tensor tractography, the trunk- and hand fibers were depicted in all and in 3 hemispheres, respectively (Figs. 2 and 4); none of the fibers of the LE, face, or tongue were depicted. With multi-tensor tractography, fibers from all 5 regions were depicted in all 10 hemispheres (Figs. 3 and 4), although the tract ratio of the LE/face/tongue regions was lower than that of the trunk or hand areas.

The mean ± standard deviation of the tract ratio of the non/trunk area on single-tensor tractograph

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Fig. 1. a: We placed regions of interest (ROIs) at 5 different locations along the primary motor cortex to depict the different fiber tracts of the corticospinal tract on a $b = 0$ diffusion-weighted image (DWI). b: We placed the ROI of the pons on a diffusion-tensor image (DTI) color map.

Fig. 2. Single-tensor tractography
Summary of the tract ratio of each fiber bundle in a hemisphere. This method is limited to the depiction of the trunk and hand regions. rt: right, lt: left

Fig. 3. Multi-tensor tractography
Summary of the tract ratio of each fiber bundle in a hemisphere. Fibers from various locations are depicted, but the tract density of the lower extremity/face/tongue areas is lower than that of the trunk or hand area. rt: right, lt: left

was $2.4 \pm 4.4\%$ and on multi-tensor tractograph, $25.0 \pm 9.4\%$. The mean tract ratio of the non-trunk area was significantly greater on multi- than single-tensor tractograph ($P < 0.0001$).

Discussion

Our study showed that though multi-tensor tractography allows visualization of nerve fibers from all areas of the primary motor cortex, only fibers from the trunk and hand regions are visualized on single-tensor tractography. The depiction of non-trunk fibers was significantly better with multi- than single-tensor tractography. Limited visualization of the fibers with the single-tensor method is probably attributable to the presence of the major fiber bundles, such as the superior longitudinal fascicles and callosal fibers, that cross the motor tract at the level of the centrum semiovale.

Yamada’s group\(^{11}\) reported that multi-tensor tractography using a $b$-factor of 1000 s/mm\(^2\) and a 1.5T MR scanner can depict the fiber tracts from the face and tongue regions. However, use of their method in the clinical setting is limited because their acquisition time exceeded 14 min with 2 acquisitions. We employed a 3T MR scanner with a short acquisition time (approximately 7 min), and because we depicted fibers from the 5 regions in all 10 hemispheres, our method appears to be more robust than theirs with respect to the depiction of the non-trunk regions. We attribute our shorter acquisition time to the high SNR at 3T scanning\(^{17-20}\) and suggest that it is short enough to permit application of the multi-tensor technique in the routine clinical setting. Although there are more susceptibility artifacts and distortions using high field MR
Fig. 4. Depiction of each fiber tract on single- and multi-tensor tractography in the left hemisphere of a 23-year-old man (Case 2). Coronal (a) and axial (b) views of single-tensor- (left) and multi-tensor tractography (right) on a b = 0 diffusion-weighted image (DWI). Single-tensor tractography is limited to the depiction of the trunk region. Multi-tensor tractography depicts fibers from all 5 locations; the fiber ratio for the lower extremity was 4%; the trunk, 78%; the hand, 10%; the face, 7%; and the tongue, 1%.

scanners, DTI acquisition with a parallel imaging technique has been shown to lessen these problems.\textsuperscript{26,27} In our study, we incorporated the parallel imaging technique.

The combination of the HARDI technique with a high b-value is suitable.\textsuperscript{13-16} However, use of a high b-value lowers the SNR on images and increases acquisition time, which conflicts with the need for a "clinically feasible" acquisition time. Therefore, we used the standard b-value of 1000 s/mm\(^2\), which somewhat facilitated the resolution of crossing fibers. Further study is needed to determine if use of a higher b-value might improve the depiction of the LE, face, and tongue fibers.

Our study has several limitations. First, the single-tensor model offers almost instantaneous calculation of the tensor dataset, which allows the start of fiber tracking soon after completion of data acquisition. However, the multi-tensor technique requires more complex data-fixing, and the longer calculation time needed for post-processing may render its intraoperative use difficult.

Second, at present, MR tractography is a user-defined process. The choice of different parameters may produce different fibers, and the tracked volumes depend on the size and location of the seed ROIs. Although the results of our comparative study may have been biased by these limitations, the size and location of the seed ROIs were the same in our single- and multi-tensor models.

Third, our sample size was small, and studies on larger populations that include patients are necessary to evaluate the feasibility of the clinical use of the multi-tensor technique.

Conclusion

At 3T, HARDI-based multi-tensor tractography using a standard b-value, could depict fibers from wider areas of the motor cortex than single-tensor tractography. Further investigations in large study populations are required to determine the useful-
ness of multi-tensor tractography in a clinical setting.

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