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Early Visual Pathway Revealed by Combined Noninvasive MEG and Diffusion MRI

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ABSTRACT

Knowledge of the functional roles of brain areas and associated connections is important to understanding brain processing. To our knowledge, this was the first internal study to apply combined high-temporal-resolution magnetoencephalography and high-spatial-resolution diffusion magnetic resonance imaging of the brain. This multimodality technique is useful for determining whether tractographic paths actually convey functional information and whether the locations of magnetoencephalography dipoles have anatomic correlates. Applying our technique to the visual pathway indicated that fibers generated from an equivalent current dipole near the calcarine fissure could be successfully tracked to the lateral geniculate nucleus and corpus callosum. The obtained results indicate that combining different imaging techniques might open a new window for studying various lesions in the visual pathway.

INTRODUCTION

Many recent studies have explored anatomical and functional connections in the brain [1, 2, 3, 4]. Recent advances in magnetic resonance imaging (MRI) methods

have given new opportunities for combining these two types of brain information [5, 6, 7]. Diffusion MRI (dMRI), which is based on anisotropic water diffusion within brain tissue, has an important application in anatomic fiber tracking. In contrast, magnetoencephalography (MEG) allows functional brain imaging in real time, providing an almost undistorted view of the magnetic fields induced by neuronal activity. Therefore, the aim of this study was to combine these two complementary noninvasive approaches as detecting visual evoked dipole sources by MEG and q-ball tracking fibers by dMRI to facilitate an in-depth exploration of neuroscience mechanisms. This combined mapping technique is useful for determining whether tractographic paths actually convey functional information and whether the locations of MEG dipoles have anatomic correlates.

MATERIALS AND METHODS

To check that the tracks were identified exactly, the conventional early visual pathway was used due to it being well understood. Human brain q-ball imaging (QBI) was performed in vivo by a GE Healthcare Signa 1.5-T Excite scanner at Taipei Veterans General Hospital using a spin-echo echo-planar imaging sequence with 162 icosahedral diffusion-encoding directions, matrix size = 128 × 128, slice number = 46, voxel size = 2.0 × 2.0× 2.2 mm^3, TR/TE = 13600/91.2 ms, and bmax = 3000 s mm^{-2}. For each MRI voxel, the orientation distribution function (ODF) was reconstructed by the Funk-Radon transformation [8]. The tracking algorithm applied in this research was MFACT (multiple fiber assignment by continuous tracking), which is similar to FACT proposed by Mori and van Zijl [9] but can be applied to the propagating fiber spread for diffusion data with a high angular resolution. Tracking terminated when the local maximum of the ODF was lower than 0.7 or when the diffusion direction in consecutive steps differed by more than 50 degrees. Reconstruction techniques for QBI, fiber tracking, and visualization were developed in-house using Borland C++ Builder 6 and OpenGL API.

For the visual stimulation, a single wedge-shaped checkerboard pattern was presented binocularly in the right hemifield in an “on” and “off” mode. Subjects were instructed to fixate on a small red cross presented in the central field so as to minimize eye movements during the experiment whilst not performing other tasks. Visual evoked fields were recorded with a whole-head 160-channel coaxial gradiometer (PQ1160C, Yokogawa Electric, Tokyo, Japan). One hundred epochs of 200-ms duration (including a 100-ms prestimulus period for baseline correction)

were averaged. The position of the subject's head relative to the MEG sensor was measured using a three-dimensional digitizer and five markers. MEG–MRI coregisteration procedures have been reported elsewhere [10]. In the source analysis, a single equivalent current dipole (ECD) model in a spherical volume was applied to estimate the cortical source of the measured magnetic fields. Further steps involved in source modeling were performed using Curry V5.0.8 software (Neuroscan, El Paso, Texas). The ECD with the highest value [exceeding 85% of the goodness-of-fit (GOF) value] was selected as a volume of interest in QBI. The conventional early visual pathway was used for comparison to ensure that the tracks were identified exactly.

RESULTS

Fig. 1 shows the results of whole-brain white-matter tractography as a color fiber orientation map. The location of the ECD at 104 ms (Fig. 2) with the highest GOF value (95%) was used as a seed point for segmenting specific connections within the entire map. Those fibers shown in red in Fig. 3a were superposed on the visual pathways (fiber bundles coded by pink), which were propagated from the intact V1 area by using MFACT. A schematic of the well-known anatomy of the visual pathway is also presented in Fig. 3b for comparison.

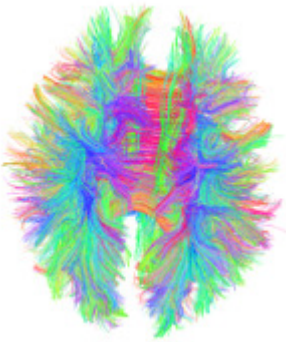

FIG. 1. Whole-brain tractography.

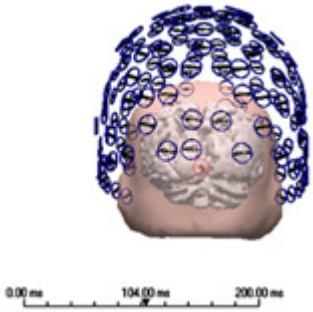

FIG. 2. A rear view of the segmented cortex with the ECD of M100 indicated in red.

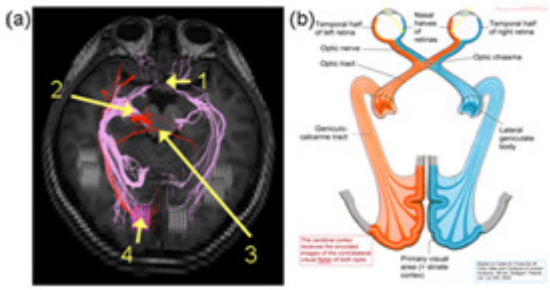

FIG. 3. (a) Tracking fibers from the dipole at 104 ms are superposed onto the early visual pathway. The red fibers are the tracking result from the seed-point dipole fitted around the calcarine fissure. The pink fibers are the early visual pathway tracks from the whole V1 area. (Numbers 1 to 4 indicate chiasma, LGN, corpus callosum, and V1, respectively.) (b) Anatomy of the visual pathway (http://instruct.uwo.ca/anatomy/530/530notes.htm).

DISCUSSION AND CONCLUSION

To our knowledge, this was the first internal study to apply combined high-temporal-resolution magnetoencephalography and high-spatial-resolution diffusion magnetic resonance imaging of the brain. As comparing to the anatomy of early visual pathway, fiber bundles (*e.g.,* optic chiasma, optic tract, and optic radiation) in the posterior visual pathway were clearly demonstrated. In the visual pathway there is a point-to-point projection, also called the retinotopic map, from the retina relaying to the lateral geniculate nucleus (LGN) and then to the visual or “striate” cortex (V1). This is a very specific overlay of projections from the two eyes, so that the left LGN and the right LGN receive information from the right and left visual fields, respectively [11]. Similarly, in our results, fibers generated from an ECD appearing near the calcarine fissure could be successfully tracked to the left LGN and the corpus callosum. The obtained results indicate that combining different imaging techniques might open a new window for studying various lesions in the visual pathway and lay a foundation for the further exploration of complex brain structures.

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FOOTNOTES

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