MR Imaging for Sportology; Non-Invasive Visualization of the Brain and Muscles

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Recent advances of MR imaging allow us to visualize the functional and structural changes of the brain not only in the patients with neurological disorders, but also in normal subjects. Sophisticated MR techniques, such as resting-state functional MR and diffusion MR imaging, can depict subtle brain changes in normal subjects before metabolic syndrome as well as brain changes after a few weeks muscle training. Minimal structural changes in the brain after repeated minor head trauma during sports are now highlighted, because advanced MR techniques can be used to show substantial changes in the brain before neurological decline.

By diffusion tensor imaging (DTI), we can explore microstructure of the tissue *in vivo* through analysis of water diffusion direction and restriction. DTI was developed mainly in the central nervous system to visualize the white matter tracts and their networks. Plasticity of the brain white matter has been reconfirmed with this technique. Skeletal muscles also have the direction and restriction of water diffusion and can be analyzed by DTI as well.

Recent advances of MR techniques for sportology, especially diffusion MR imaging, will be presented in this paper.

Key words: sportology, diffusion tensor imaging, MR imaging

Introduction

Recent advances of MR imaging (MRI) allow us to evaluate subtle changes of the human brain *in vivo*. Functional MRI can demonstrate local activity changes related to the “task” in the brain. Tasks can be auditory, visual, motor or other complicated procedures. Changes or differences of regional brain volume can be evaluated by the voxel-based morphometry using three-dimensional T1-weighted images of MRI. MR spectroscopy represents a spectrum of several brain metabolites semi-quantitatively. Diffusion tensor imaging (DTI) or diffusion MR analysis can uniquely evaluate the white matter tracts through precise analysis of water diffusion. There are several methods to analyze brain using DTI such as tract-specific analysis (TSA), tract-based special

statistics (TBSS), and connectome. In this paper, we would like to present the usefulness of MR imaging for sportology, especially about DTI.

Quick review of diffusion tensor imaging of the brain

The white matter could not be explored precisely, because it was difficult to track the fibers using specimen. DTI is a unique technique to visualize the white matter tract. DTI has been proposed by Bassar in 1994¹⁾ and developed rapidly in these years. DTI is a model that is used to analyze the diffusion of water molecule *in vivo*, assuming the form of diffusion in one voxel as an ellipsoid (Figure-1). In the brain, diffusion of water molecules is anisotropic due to white matter fibers. Diffusion parallel to the white matter fibers is larger

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Figure-1 Diffusion tensor ellipsoid and Lambda 1, 2 and 3

than the one perpendicular to the fibers. The component of diffusion parallel to the white matter is Lambda 1 (λ_1) or axial diffusivity (Da). The component of diffusion perpendicular to the white matter is Lambda 2 (λ_2) and 3 (λ_3) (Lambda 2 and 3 are perpendicular to each other). Average of Lambda 1 and 2 is called radial diffusivity (Dr). The standardized standard deviation of Lambda 1, 2, and 3 is Fractional Anisotropy (FA). When the white matter fibers are densely packed, water molecules move mainly along (parallel to) the fibers, this is due to the myelin and other membranes. The FA value becomes high when the Lambda 1 is large, but Lambda 2 and 3 are small. Decreased FA of the white matter fibers indicates deterioration or degeneration of white matter fibers.

By tracking or chasing the Lambda 1 direction three dimensionally, we can visualize the white matter tracts^{2) 3)} (Figure-2, 3). The tracking algorithm so called FACT (Fiber Assignment by Continuous Tracking) has been proposed by Mori²⁾. Dense and thick bundles such as the corticospinal tracts, the cingulate, uncinate and fornix are clearly visualized (Figure-3). The tracts without crossing fibers are clearly visualized by DTI. Region of interest (ROI) analysis⁴⁾ and TSA^{5) 6)} are developed to quantify the tract integrity measuring parameters within the tract.

Whole brain statistical analysis can be implicated in DTI data. The statistical parametric map (SPM) is widely used for functional MRI analysis and can

also be used for DTI analysis. TBSS (tract based special statistics)⁷⁾ is a newly developed technique to analyze DTI and other diffusion MR imaging. Using whole brain statistical analysis, we can explore regional brain abnormalities without the hypothesis of locations (Figure-4).

Non-Gaussian diffusion analysis is now highlighted to analyze precise microstructures using multi-shell (v-value) multi-MPG (>30) MR acquisition⁸⁾.

Plasticity of brain by training

Changes of the brain after training or exercise that seen by brain MRI had been reported in several conditions. Aerobic exercise training increases brain volume in aging humans⁹⁾. Volume changes of both gray and white matter, especially on the frontal lobe was observed. Changes of volume in one year had been reported (VOSS HBM). Significant increase of Fractional Anisotropy (FA) of DTI also had been observed.

Plasticity of the brain has been presented by using DTI after training of three-ball juggling¹⁰⁾. After 6 week hard training of juggling, increase of whole brain FA, especially at the right parietal lobe, probably related to special recognition, was observed. In addition, after 4 week rest, this increased FA was decreased.

Early plasticity of the brain after learning can be evaluated as well¹¹⁾. Changes of DTI parameters of

Figure-2 Diffusion tensor tractography of the whole brain

Figure-3 The limbic system and corticospinal tracts are the tracts that can be visualized consistently by diffusion tensor tractography

Figure-4 Brain changes in matabolic syndrome: TBSS analysis. The corpus callosum and external capsule showed significant deterioration. The external capsule was actually the inferior longitudinal fasciculus. (Shimoji K, *et al*: Diabetes Care, 2013; 36: 696-700¹³⁾)

limbic system (hippocampus and para-hippocampus) were observed after spatial learning and memory task.

Diffusion tensor imaging of metabolic syndrome

Changes of the brain in individuals with metabolic syndrome have been explored by TBSS^{12) 13)} (Figure-4). TBSS revealed a significant decrease of FA in the corpus callosum and the right longitudinal fasciculus. TSA of the right longitudinal fasciculus showed significant correlation between FA of the tract and body-mass index. These changes of the long tract might be related to faint deterioration, possibly related to metabolic syndrome.

Diffusion tensor imaging and minor trauma

Subtle changes of the minor brain trauma of athletes such as in soccer and American football have been highlighted. National football league in the United States and General Electric had a big project called Head Health Challenges. This project focuses on the development of technologies that can detect early stage mild traumatic brain injuries. Many papers about minor head trauma or concussion have been published recently. It is because of the development of new imaging methods, especially DTI.

Diffusion tensor imaging has been used to evaluate minor trauma due to sports. Subtle changes of repeated heading during soccer have been reported. The quantity of heading prior 12 month and DTI of 37 amateur soccer players were evaluated. "FA at three locations in the temporo-occipital white matter is lower, with a threshold that varied according to location (885-1550 headings per year) ($p < .00001$). Lower levels of FA were also associated with poorer memory scores ($p < .00001$), with a threshold of 1800 headings per year."¹⁴⁾ Changes of DTI metrics of the individual subjects after sports-related concussion has been reported¹⁵⁾.

DTI outside the brain

Diffusion tensor imaging can be used to visualize the complexity of the muscle structures. The bundles of the muscles can be clearly demonstrated

using diffusion tensor tractography. Change of apparent diffusion coefficient has been observed even in the Trunk muscles between before and after training¹⁶⁾.

Change of diffusion tensor parameters after long-distance running (marathon) also has been reported¹⁷⁾. Marathon runners were scanned before, 2 days after and 3 weeks after marathon. Change of DTI parameters was observed in different muscles in different degrees at the level of upper leg¹⁷⁾.

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