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Altered white matter architecture among college athletes: A diffusion tensor imaging study

SHEN Guo-hua[1], ZHANG Jian[2], WANG Hui[1], WU Yin[2], ZENG Yu-wen[2], DU Xiao-xia[1]

(1. *Shanghai Key Laboratory of Magnetic Resonance, Department of Physics, East China Normal University, Shanghai* 200062, *China*;
2. *Shanghai University of Sport, Shanghai* 200438, *China*)

Abstract: Previous studies have shown that motor skill learning can induce changes involving the structural reorganization of gray and white matter architecture. However, whether learning basketball-related motor skills activates structural plasticity in the cerebral white matter is presently unknown. We used diffusion tensor imaging (DTI) to assess microstructural differences within the white matter of college basketball athletes and non-athletes. In all, 15 healthy college basketball athletes and 15 healthy college non-athletes took part in the experiments. Tract-based spatial statistics (TBSS) were used to perform a whole-brain analysis of the DTI data and to explore brain structural differences between athletes and non-athletes. Compared to non-athletes, athletes demonstrated significantly greater FA in the right middle temporal gyrus, bilateral middle occipital gyrus, right middle frontal gyrus, right frontal lobe, right precentral gyrus, left insular cortex and parahippocampal gyrus. These areas are all involved in learning motor skills and sports training. The results imply that there is an association between sports training and subsequent white matter changes.

Key words: motor training; diffusion tensor imaging; white matter; athletes

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大学生运动员脑白质的变化: 基于磁共振扩散张量成像研究

沈国华[1], 张 剑[2], 王 慧[1], 吴 殷[2], 曾雨雯[2], 杜小霞[1]

(1. 华东师范大学 物理系 上海市磁共振重点实验室, 上海 200062; 2. 上海体育学院, 上海 200438)

摘要: 前人的研究发现运动技能的学习能够导致脑白质和灰质结构发生相应的改变. 然而长期的篮球技能的学习是否能导致脑白质可塑性的变化, 目前还不明确. 本文利用磁共振扩散张

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第一作者: 沈国华, 男, 博士研究生, 研究方向为磁共振成像. E-mail: wintersgh@163.com.

通信作者: 杜小霞, 女, 副教授, 硕士生导师, 研究方向为磁共振成像. E-mail: xxdu@phy.ecnu.edu.cn.

量成像研究了大学生篮球运动员和非运动员之间脑白质的差异. 一共15名大学生篮球运动员和15名非运动员参与本次实验. 利用FSL软件和TBSS方法分析磁共振数据，从而获得两组人群脑白质的差异. 研究结果显示, 相比非运动员, 篮球运动员脑白质中的水分子扩散系数的各向异性参数FA表现为局部升高; 这些显著升高的区域主要在右侧颞中回、双侧枕中回、右侧额中回、右侧额叶部分区域、右侧中央前回、左侧岛叶和海马旁回. 而这些有变化的脑区域均参与运动训练和运动技能的学习. 研究结果提示, 这些脑白质的改变和运动训练存在内在的关联.

关键词: 运动训练; 扩散张量成像; 白质; 运动员

0 Introduction

Previous research has shown that motor skill learning/training can induce plastic changes involving the structural reorganization of the gray and white matter architecture [1]. Several studies reported that greater gray matter volume was found in the sensorimotor cortex, cerebellum, premotor cortex [2,3] and auditory cortex [2,4] of musicians compared to non-musicians. It was also reported that white matter differs between musicians and non-musicians [3,5,6]. Cannonieri et al. also found that long-term, bimanual training may increase the gray matter volume in the brains of professional typists [7]. Regarding golfers, greater gray matter volume was found in the premotor and parietal areas of skilled golfers, while the white matter architecture changed in both the internal and external capsule and in the parietal operculum [8]. The study of Bezzola et al suggested that golf training induces adaptations in the gray matter of golf novices [9]. Park et al reported that the gray matter volume was different in the vermian lobules of the cerebellum between basketball players and controls [10]. However, whether learning and training basketball-related motor skills activates structural plasticity in the cerebral white matter is presently unknown.

Diffusion tensor imaging (DTI) is an MRI method that is a useful means to study the white matter anatomy of the human or animal brain in vivo. Fractional anisotropy (FA) value is the most common diffusion parameter, which quantifies the directionality of diffusion within a voxel between 0 (isotropic) and 1 (anisotropic)[11]. FA values are most often used to characterize the integrity of white matter tracts. It has been found that FA value was associated with cognitive function[12,13]. Previous research has indicated that FA increases with age from childhood to adolescence[14,15]. Reduced FA is often regarded as an index of decreasing white matter health, and FA has been reported to decrease in neurodegenerative diseases such as dementia [16] and primary nocturnal enuresis [17]. DTI has been used to study the plastic changes in white matter architecture due to long-term practice. For example, using DTI, Bengtsson et al found positive correlations between practicing and fiber tract organization, these results suggest that training can induce white matter plasticity[6].

Athletes are a useful group for the study of neural plasticity of extensive long-term training. Professional athletes begin sports training in childhood, practicing several hours every day. Hours of daily sports training over many years may induce plastic changes in the human brain, which is an ideal model for the study of plastic changes in the white matter architecture as a result of long-term practice.

Generally, college athletes are regularly exposed to sports but not excessive motor training. Recently, several studies have shown a decrease of FA value in some athletes due to cumulative (chronic) brain injury or sports-related concussion[18]. We hypothesize that moderate exercise may induce plastic changes in white matter, which may be different from sports-related concussion. Further, we hypothesize that moderate exercise contributes to good health and white matter development in childhood and adolescence.

In this study, we used TBSS (tract-based spatial statistics, part of FMRIB software library (FSL)) to perform a whole-brain analysis of the data and to explore structural differences in the brains of athletes versus non-athletes.

1 Materials and methods

1.1 Subjects

All participants involved in our study provided written informed consent before the experiments. The consent procedure was approved by the ethics committee of Shanghai University of Sport.

Fifteen basketball players (national second-level athlete) aged 18–21 years (mean=19.6 years, s.d.=1.3) and fifteen students with no experience playing basketball (no sports specialty and everyday average less than half an hour of physical exercise) aged 17–21 years (mean=19.3 years, s.d.=1.8) took part in the study. All participants were men, and all were right-handed according to a standard handedness inventory. The basketball players were recruited from the basketball team of Shanghai University of Sport; they trained 7 h (s.d.=1.7) per week and had played basketball for 3–10 years (mean=6.4 years, s.d.=1.9). None of the participants had neurological, psychiatric, or other medical problems. To determine the history of sports-related concussion, athletes were interviewed, subjected to an MRI scan, and excluded from the study if necessary.

1.2 Data acquisition

MRI data were acquired on a Siemens 3T Trio MR scanner with a 12-channel phased array coil. Firstly, each subject underwent anatomical scans with turbo spin echo T_2-weighted pulse sequence (TR/TE=6 000/93 ms, slice thickness=4 mm, 32 slices) and a saggital T_1-weighted 3D image with a magnetization prepared rapid gradient echo (MPRAGE) sequence (TR/TE=2 300/2.98 ms, TI=900 ms, slice thickness=1 mm, 160 slices). There were no visible abnormalities of T_1-weighted and T_2-weighted images in any subject.

Then, the DTI acquisition used a single-shot spin-echo echo planar imaging sequence in contiguous axial planes covering the whole brain. The diffusion sensitizing gradients were applied along 30 non-collinear directions together with an acquisition without diffusion weighting (b=0). The imaging parameters were set to the following values: TR=8 100 ms, TE=93 ms, average=2, b=1 000 s/mm^2, slice thickness=2 mm, and total slices=60. The initial matrix size was 128×128, and it was reconstructed to 256×256. The original resolution was $2 \times 2 \times 2$

mm^3, and it was interpolated to $1 \times 1 \times 1$ mm^3. The subjects were told not to move during the scans, and the DTI acquisition time was 8 minutes and 48 seconds.

1.3 Data processing and statistical analysis

Preprocessing

We mainly used the FSL 4.1 (http://www.fmrib.ox.ac.uk/fsl/) to carry out the DTI data preprocessing, which consists of the following steps: First, the FSL's "eddy current correction" was used to correct the distortion induced by the eddy current and head motion in the dataset. Second, nonbrain tissue and background noise were removed from DTI image using BET (Brain Extraction Tool, part of FSL, http://fsl.fmrib.ox.ac.uk/fsl/bet2/). Finally, the FA maps were created with DTIFit (part of FSL, http://www.fmrib.ox.ac.uk/fsl/fdt/fdt_dtifit.html).

TBSS analysis

A whole brain voxel-wise analysis was performed using TBSS (tract-based spatial statistics, part of FSL).

(1) The FA maps of all subjects were first realigned to a common target brain image template (FMRIB58_FA). Through this procedure, all the FA volumes were normalized to a $1 \times 1 \times 1$ mm^3 Montreal Neurological Institute (MNI152) standard space.

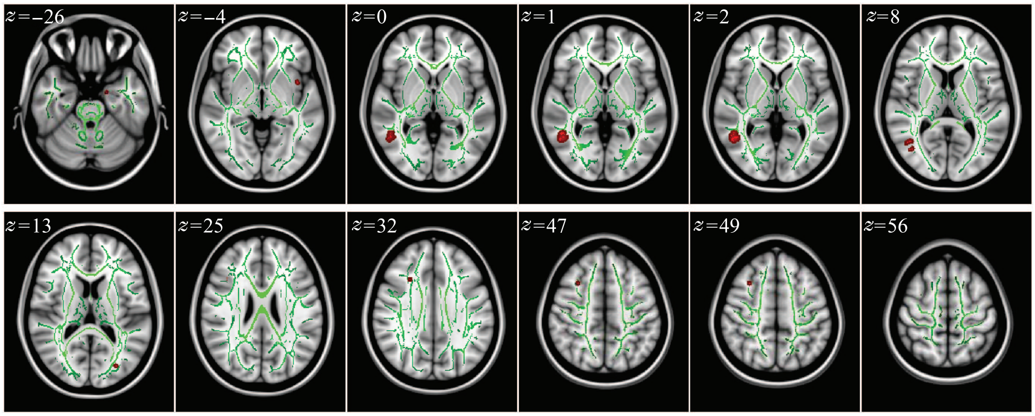
(2) The registered FA images were averaged to generate a cross-subject mean FA image, and then, the mean FA image was thinned to create a mean FA skeleton representing the main fiber tracks and the center of all fiber tracts common to the two groups (athlete group and control group).

(3) The mean FA skeleton was subjected to a threshold of 0.2 in order to exclude peripheral tracts resulting from excessive cross-subject variability and registration misalignments. Following this threshold application, the aligned FA data of each participant was projected onto the mean skeleton to create a skeletonized FA map.

Threshold-free cluster enhancement (TFCE) was used to analyze significant differences between the two groups, with $p < 0.005$ as the threshold for statistical significance (uncorrected). On the basis of the results of voxel-wise group comparisons, the skeletal regions showing significant inter-group differences were located and labeled anatomically by matching the statistical map to the Johns Hopkins University (JHU)-ICBMDTI-81 white matter labels atlas, JHU-WM tractography atlas, Harvard-Oxford cortical structural atlas and Harvard-Oxford subcortical structural atlas in MNI space.

2 Results

A significant increase in FA was revealed in the athletes by TBSS. Compared to non-athletes, college athletes demonstrated significantly greater in FA in the right middle temporal gyrus, bilateral middle occipital gyrus, right middle frontal gyrus, right frontal lobe (sub-gyral), right precentral gyrus, left insular cortex and parahippocampal gyrus. No decreases in FA value were found in the athletes compared to the non-athletes. Detailed results are shown in Figure 1 and Table 1.



Note: Areas in red were regions where FA was significantly increased ($p < 0.005$, uncorrected) in athletes relative to non-athletes. To aid visualization, regions showing increased FA (red) were thickened using the tbss_fill script implemented in FSL. The results were shown overlaid on the MNI152-T1 template and the mean FA skeleton (green). The left side of the image corresponded to the right hemisphere of the brain.

Fig. 1 TBSS analysis of fractional anisotropy (FA) images

Tab. 1 Results from the TBSS analysis of fractional anisotropy (FA) between athletes and non-athletes

Anatomic region	Hemisphere	MNI coordinates/mm			p value[a] (minimum)	Cluster size /mm^3
		X	Y	Z		
Middle temporal gyrus/WM/SLF	R	51	−54	2	0.002	14
Middle temporal gyrus/WM/ SLF	R	49	−60	2	0.002	14
Middle temporal gyrus/WM/SLF	R	46	−52	1	0.002	14
Middle temporal gyrus/WM/SLF	R	51	−59	1	0.002	14
Middle temporal gyrus/WM/SLF	R	49	−51	0	0.002	14
Middle temporal gyrus/WM	R	49	−55	0	0.002	14
Middle occipital gyrus/WM	R	43	−69	8	0.002	11
Middle occipital gyrus/WM	R	41	−69	8	0.005	6
Middle occipital gyrus /WM/ILF/IFOF	L	−28	−79	13	0.002	7
Middle frontal gyrus/WM /SLF	R	31	14	49	0.002	12
Middle frontal gyrus/WM /SLF	R	31	15	47	0.005	12
Middle frontal gyrus /WM	R	40	20	25	0.005	8
Frontal lobe/sub-gyral /WM	R	27	19	32	0.005	9
Precentral gyrus /WM/SMA	R	9	−21	56	0.005	5
Insular cortex/GM	L	−39	7	−4	0.002	13
Parahippocampal gyrus	L	−18	−4	−26	0.002	10

Note: [a]For peak voxel of the cluster; R right side, L left side, WM gray matter, GM gray matter, SLF superior longitudinal fasciculus, ILF inferior longitudinal fasciculus (connects the temporal lobe and occipital lobe), IFOF inferior frontal-occipital fasciculus, SMA supplementary motor areas.

3 Discussion

The study demonstrated that college basketball players have plastic changes of white matter architecture in the right middle temporal gyrus, the bilateral middle occipital gyrus, the right middle frontal gyrus, the right frontal lobe (sub-gyral), the right precentral gyrus，the left insular cortex and the parahippocampal gyrus. These basketball players were trained 7 h per week and without brain injury or sports-related concussion, they showed the great FA values in several brain areas. The results suggest that the white matter undergoes plasticity may be induced by regular sports training throughout childhood. However, FA was decreased in some athletes with cumulative (chronic) brain injury or sports-related concussion[18]. As we hypothesize that moderate exercise would induce plastic changes in white matter. In the other words, moderate exercise may contribute to good health and white matter development in childhood and adolescence.

3.1 Middle temporal gyrus

The most significant cluster revealed by TBSS was the increase in FA observed in the white matter of the middle temporal gyrus, most of which is contained within the superior longitudinal fasciculus (SLF).

Generally, the superior longitudinal fascicle is considered to be a major association fiber pathway connecting the parieto-temporal association areas with the frontal lobe. In humans, the SLF can be divided into four components: SLF I, SLF II, SLF III and the arcuate fascicle (AF)[19]. In our results, the cluster was probably located in the AF[19]. The fibers of the AF connect the temporal lobe with the prefrontal area. This pathway has been suggested to receive auditory spatial information[19-21]. Therefore, the AF may provide a means for prefrontal cortex to receive and modulate audiospatial information[19]. The increased FA in the temporal lobe was suggested that athletes may be quicker to receive and modulate auditory spatial information.

3.2 Middle occipital gyrus

The results showed that FA increased significantly in the white matter of the middle occipital gyrus. The occipital lobe is well known to be the visual processing center of the human brain. A meta-analysis demonstrated that the right middle occipital gyrus is critically involved in unilateral spatial neglect[22]. We observed an increase in FA within the white matter of the left middle occipital gyrus, including the inferior frontal-occipital fasciculus and part of the inferior longitudinal fasciculus, which connects the temporal and occipital lobes.

FA was increased in the white matter of the middle occipital gyrus in athletes, suggesting that the occipital lobe in athletes may be more efficient at processing visual information and that it could exchange information more rapidly with other brain regions. The plasticity changes may be derived from many years of basketball training, which led to better performance in basketball games than non-athletes.

3.3 Frontal lobe

The results also indicate that athletes have an increased FA in the frontal lobe, including the white matter of the middle frontal gyrus (such as SLF), the white matter of the sub-gyral and supplementary motor areas.

The frontal lobe includes the premotor and primary motor cortices and plays an important role in the planning, control and execution of voluntary movements. The supplementary motor area is a part of the primate cerebral cortex that contributes to the control of movement. The cluster in the white matter of the middle frontal gyrus also belongs to the SLF and is probably located in SLF I[19]. SLF I appears to originate from the medial and dorsal parietal cortex and ends in the dorsal and medial part of the frontal lobe[19]. SLF I, by virtue of its interconnection with medial and superior parietal regions, the supplementary motor area, and the dorsal premotor region, can contribute to the regulation of higher aspects of motor behavior[19]. Increased FA in the frontal lobe of athletes may improve their flexibility and accuracy while playing sports.

3.4 Other regions

Finally, we found two peak areas with FA increase in the insular cortex and parahippocampal gyrus. The insular cortex has been reported to be involved in motor control[23]. The parahippocampal gyrus plays an important role in the encoding and recognition of scenes and contributes to human spatial navigation[24]. FA increase in these two brain areas is likely due to sports training.

Additionally, The results show differences occurring mainly in the right hemisphere. One review discussed right hemisphere dominance for visuospatial processing and representation in humans[25]. Sports training may improve the ability of visuospatial processing in athletes and induce white matter plasticity mainly in the right hemisphere.

4 Conclusions

In summary, The results revealed plasticity changes of the white matter, which were all involved in learning motor skills and sports training; therefore, the results imply that there were an association between sports training and subsequent white matter changes.

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