Short-term meditation increases network efficiency of the anterior cingulate cortex

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Previous studies have found that short-term integrative body–mind training (IBMT) has positive effects on the brain structure and function in the anterior cingulate cortex. Here, we determined whether 11 h of IBMT alters topological properties of the anterior cingulate cortex in brain functional networks. We applied network analysis to resting-state functional connectivity between 90 cortical and subcortical regions before and after IBMT and relaxation training. The results demonstrated a significant increase in the network efficiency and connectivity of the anterior cingulate cortex after IBMT, but not after relaxation training. These findings indicated that the change in network topology might occur by altering the brain or psychological state. IBMT might be an intervention tool for improvement of self-regulation. *NeuroReport* 00:000–000 © 2011 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

Meditation has recently received considerable attention as a potential approach to prevention and intervention in mental disorders [1]. Many studies have reported the beneficial effects of meditation on brain structure and function, such as an increased default-mode network connectivity [2], reorganization of cognitive resources [3], increased regional cortical thickness [4], and grey matter densities [5,6]. In our previous studies, integrative body–mind training (IBMT) has been proven to improve attention and self-regulation [7], reduces stress as measured by cortisol secretion after a stressful experience [8,9], improves the basal immune system in a dose-dependent manner [10], and induced white matter changes in fractional anisotropy in the anterior corona radiata, a white matter tract associated with the anterior cingulate cortex [11].

Quantitative analysis in a framework of complex networks based on graph theory is becoming increasingly useful for understanding human brain structure and function [12]. Recently, brain networks derived from different modalities of neuroimaging data have been consistently reported to exhibit nonrandom organization patterns, including high efficiency of information transfer for low wiring costs [13]. Such networks are thought to provide the physiological basis for the efficiency of information processing and mental representations [12]. Importantly, changes of topological properties in brain networks have been observed to be associated with mental disorders [14] and cognitive fitness [15].

The anterior cingulate cortex is a key regional node of the human brain's self-regulatory network, integrating inputs from diverse sources to regulate responses and to guide behavior [16]. As such, its alterations may provide a mean for cognitive, emotional, and social improvement. Here, we extend our work using resting-state functional magnetic resonance imaging (fMRI) and graph theory methods to determine whether short-term IBMT improves the efficiency of information processing by altering the topological properties of the anterior cingulate cortex in brain functional networks at rest.

Methods

Participants

We obtained written informed consent from 32 healthy Chinese undergraduates at Dalian University of Technology (17 women and 15 men; mean age = 21.44 years; standard deviation = 1.59) without any previous meditation or relaxation experience. Participants were randomly assigned to an experimental group (IBMT) and a control group [relaxation training (RT)]. Fifteen experimental participants (eight women) practiced 30-min IBMT from Monday to Friday for 1 month, with a total of 11 h of training; whereas 17 controls (nine women) received the same amount of RT. The trainees concentrated on achieving a balanced state of body and mind guided by an IBMT coach and the compact disc, whereas the control group focused on muscle relaxation guided by a tutor and compact disc [7–9]. All participants were right-handed native speakers of Chinese, with no history of neurological or psychiatric disorders, and received no psychotropic medications or medicinal herbs, without experiencing any severe or prolonged negative life events based on their self-report. The experiment was approved by the local Institutional Review Board.

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Data acquisitions

Brain images were acquired on a 3.0 Tesla Philips Achieva MR imaging system (Philips Achieva, Best, Netherlands). MRI images of the whole brain using an echo-planar imaging sequence were collected in 36 slices (repetition time = 2000 ms, echo time = 30 ms, flip angle = 80°, field of view = 23 cm, matrix = 64 × 64, 4-mm thickness, and 0-mm gap). During a 6-min scan session, the participants were instructed to fixate on a small white crosshair located in the center of a black screen and remain motionless.

Data preprocessing

Images preprocessing and further analysis were performed by Statistical Parametric Mapping software (SPM8; *www.fil.ion.ucl.ac.uk/spm*) and resting-state fMRI data analysis toolkit (*http://resting-fmri.sourceforge.net*). For each dataset, the first 10 images were discarded to allow for magnetization equilibration effects and the adaptation of the participants to the circumstances. The remaining images for further preprocessing were first corrected for time delay between slices, and then were realigned to the first volume for head-motion correction. The realigning step provided a record of head motions by estimating the translations in each direction and the rotations in angular motion about each axis for each of the consecutive volumes. All the participants included in the study exhibited a maximum displacement of less than 1 mm at each axis and an angular motion of less than 1° for each axis. After the correction, the images were normalized into a standard stereotactic space as defined by the Montreal Neurological Institute (resampling voxel size = $2 \times 2 \times 2\,\text{mm}^3$), and smoothing with an 8-mm Gaussian kernel, full width at half maximum. Finally, temporal band-pass filtering (between 0.01 and 0.08 Hz) was performed to reduce the effects of low-frequency drift and high-frequency noise.

Brain network construction

We used a widely used anatomical automatic labeling atlas [17] to parcellate each brain into 90 regional nodes, and obtained the representative time series of each individual region by averaging the resting-fMRI time series over all voxels in that region, and several sources of spurious variance including six head motion parameters, global signal, cerebrospinal fluid, and white matter were then removed from the data through linear regression for partial correlation analysis. Partial correlation can be used as a measure of the functional connectivity between a given pair of regions by attenuating the contribution of other sources of covariance. The procedure for obtaining partial correlation values here was consistent with other studies [18]. For statistical analysis, Fisher's r-to-z transformation was applied to improve the normality of the partial correlation coefficients.

The functional connectivity matrices were thresholded into a set of undirected binary matrices with a sparsity value, whose element was 1 if there was large absolute coefficient between the two brain regions, and 0 otherwise. Each adjacency matrix defined an unweighted graph G consisting of regional nodes ($N = 90$) as connected to undirected edges. A sparsity-specific threshold ensured that each network had the same number of edges or wiring cost. We selected the threshold range from 0.09 to 0.3 (with an increment of 0.01). For example, sparsity threshold of 0.09 means at a connection density equivalent to approximately 9% of the total number of possible links (4005) in a network of 90 nodes. The range of sparsity was chosen here, to allow prominent topological properties in brain functional networks to be observed [19].

Network analysis

We investigated network properties (sparsity threshold ranged from 0.09 to 0.3, with an increment of 0.01), and then focused mostly on the regional topological characteristics by two nodal measures, efficiency and degree. The degree is a basic and important characteristic of a vertex. The degree of an individual node is equal to the number of connections that link it to the rest of the network, which is also equal to the number of neighbors of the node, and is defined as follows:

$$k(i) = \sum_{i \neq j \in G} A_{i,j}, \tag{1}$$

where A is the binary adjacency matrix obtained by thresholding a partial correlation matrix. A high degree indicates that the individual node has a central role for the communication spreading within the network, as its removal would reduce sensibly the overall connectivity.

As described in previous studies [13], we can similarly define regional efficiency as the inverse of the harmonic mean of the minimum path length between an index node and all other nodes in the network. For each sparsity threshold, efficiency $E(i)$ was computed for each node:

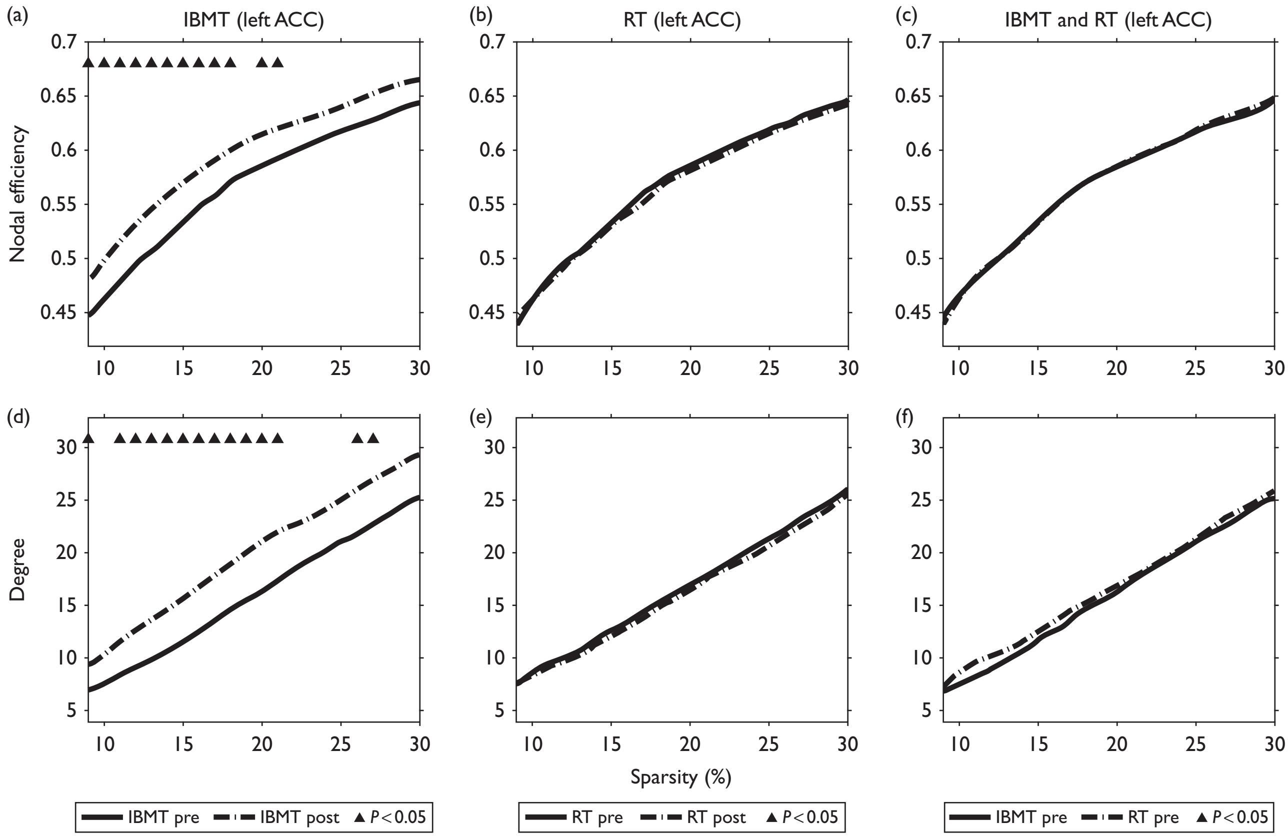
$$E(i) = \frac{1}{N-1} \sum_{i \neq j \in G} \frac{1}{L_{i,j}}, \tag{2}$$

where $L_{i,j}$ denotes the minimum path length between regions i and j. Regional efficiency measures the extent to which the node connects all other nodes of a network, its efficiency of integrated information processing, and how well information propagates over the network.

Results

We examined changes of network topological properties due to training in the anterior cingulate cortex. Before training, no differences were found for nodal efficiency

Fig. 1



(a–f) Changes of network measures in the left anterior cingulate cortex before and after integrative body–mind training (IBMT) or relaxation training (RT). Changes of network measures (y axis) are shown in the left anterior cingulate cortex as a function of sparsity thresholds (x axis) before and after 11 h of IBMT or RT. Black triangles upright indicate where the difference between the two groups is significant ($P<0.05$). ACC, anterior cingulate cortex.

between the two groups ($P > 0.05$). After 1 month of training, nodal efficiency showed a significant increase in the left anterior cingulate cortex after IBMT [$P < 0.05$, such as at sparsity threshold (15%), $t(14) = -2.437$, $P = 0.021$] but not after RT. We found no significant difference in the right anterior cingulate cortex ($P > 0.05$). In line with the efficiency findings, we found that the left anterior cingulate cortex had a greater nodal degree value after IBMT. Figure 1 shows nodal efficiency and degree in the left anterior cingulate cortex before and after IBMT or RT at the thresholds ranged from 0.09 to 0.3.

For each sparsity threshold, we sorted all 90 brain regions in a descending order of their mean efficiency values and examined changes of relative position between pretraining and posttraining. A higher-ranked position (small value) in the left anterior cingulate cortex after IBMT was found indicating that training-induced changes in the left anterior cingulate cortex were greater after 1 month of IBMT than those after RT (Table 1).

In addition, we found that a motor-related brain region in IBMT exhibited an opposite trend, with a decreased efficiency and degree found in the right supplementary motor area, but not in RT (Fig. 2).

Discussion

In this study, we used network analysis approach based on graph theory to investigate changes in topological properties of the anterior cingulate cortex by short-term meditation. The anterior cingulate cortex is a key node of the brain's self-regulation system and its changes in topological properties are likely to provide a mean for cognitive, emotional, and social improvement. Our results demonstrated an increased network efficiency and degree of the anterior cingulate cortex after 11 h of IBMT interventions. An increased connectivity degree indicated that the anterior cingulate cortex had more direct influences on other regional nodes in brain functional networks, whereas a higher efficiency of the anterior cingulate cortex could strengthen the capacity to integrate specialized information from distributed brain regions [20]. Decreased network measures [21] and reduced regional clustering [22] of the anterior cingulate cortex at rest have been associated with neurological and psychiatric disorders, thus the increased topological properties of the anterior cingulate cortex might provide a means for improvement in self-regulation by short-term meditation.

In the motor-related brain regions, the supplementary motor area is an important region involved in behavioral planning and execution [23]. Recent research on motor control has shown the supplementary motor area is closely tied to motor output [24]. In comparison with IBMT, the increased topological properties of supplementary motor area may reflect the control operations on the body muscles during relaxation training. Meditation has been reported to be essentially a physiological state of 'thoughtless awareness' [25], demonstrating a reduced metabolic activity [1]. The lower supplementary motor area efficiency and degree might be mediated to maintain the meditative state.

Table 1 **The relative position of the left anterior cingulate cortex in all 90 brain regions**

S(%)	IBMT pre	IBMT post	RT pre	RT post
9	66	19	68	67
10	67	21	67	68
11	67	17	63	70
12	70	18	69	71
13	73	17	70	72
14	72	18	70	74
15	70	13	69	74
16	66	16	70	74
17	70	16	64	72
18	60	15	65	70
19	61	14	64	71
20	65	11	62	71
21	66	12	62	71
22	64	15	63	70
23	64	14	62	71
24	63	14	61	71
25	63	16	58	71
26	66	16	62	69
27	65	15	56	69
28	65	16	58	69
29	64	19	60	66
30	63	16	56	66

The sparsity thresholds (S) range from 0.09 to 0.3, with an increment of 0.01. Other values denote the relative positions of the left anterior cingulate cortex in all 90 brain regions of an entire brain functional network ranked in order of decreasing efficiency values. Smaller value corresponds to greater efficiency. IBMT, integrative body–mind training; RT, relaxation training.

Conclusion

We adopted IBMT as a vehicle for understanding training-related brain plasticity observed in brain functional networks. Our results indicated that anterior cingulate cortex network properties during resting state were altered by short-term meditation. This may be related to previously reported improvements in self-regulation [8]. Future research is needed to explore the mechanism of changes in network properties during short-term interventions and correlated changes in brain function and performance.

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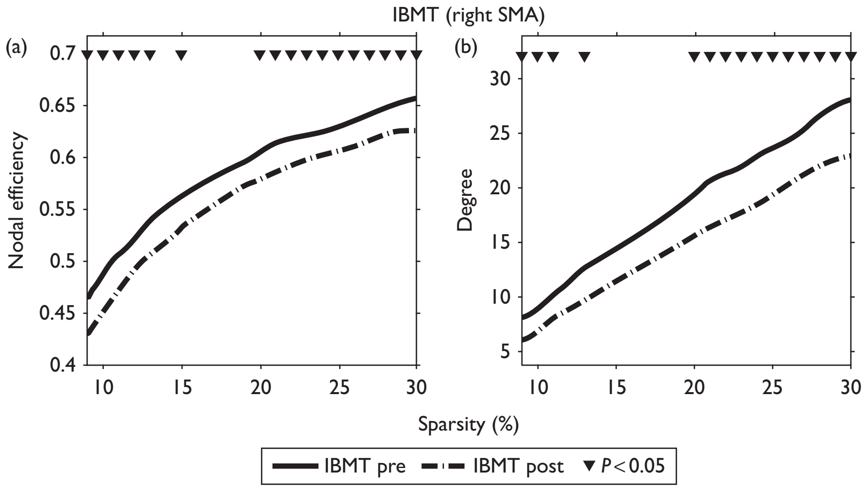
Fig. 2



(a–b) Changes of network measures in the right supplementary motor area after integrative body–mind training (IBMT). Changes of network measures (y axis) as a function of sparsity thresholds (x axis) before and after IBMT. Black triangles upright indicate where the difference between the two groups is significant ($P<0.05$). SMA, supplementary motor area.

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