Central and autonomic nervous system interaction is altered by short-term meditation

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Five days of integrative body–mind training (IBMT) improves attention and self-regulation in comparison with the same amount of relaxation training. This paper explores the underlying mechanisms of this finding. We measured the physiological and brain changes at rest before, during, and after 5 days of IBMT and relaxation training. During and after training, the IBMT group showed significantly better physiological reactions in heart rate, respiratory amplitude and rate, and skin conductance response (SCR) than the relaxation control. Differences in heart rate variability (HRV) and EEG power suggested greater involvement of the autonomic nervous system (ANS) in the IBMT group during and after training. Imaging data demonstrated stronger subgenual and adjacent ventral anterior cingulate cortex (ACC) activity in the IBMT group. Frontal midline ACC theta was correlated with high-frequency HRV, suggesting control by the ACC over parasympathetic activity. These results indicate that after 5 days of training, the IBMT group shows better regulation of the ANS by a ventral midfrontal brain system than does the relaxation group. This changed state probably reflects training in the coordination of body and mind given in the IBMT but not in the control group. These results could be useful in the design of further specific interventions.

anterior cingulate cortex | body–mind interaction | IBMT

In a previous study (1, 2), 80 Chinese undergraduates were randomly assigned to an experimental group (integrative body–mind training, IBMT) or to a control group (relaxation training) for 5 days of short-term training (20 min per day). Before training, no differences were found for behavioral, endocrine, and immune measures between the 2 groups. After 5 days of training, the IBMT group showed significantly greater improvement of performance in executive attention and positive mood, significantly reduced stress as measured by cortisol secretion following a stressful experience, and increased immunoreactivity compared to participants with the same amount of relaxation training.

IBMT was adopted from traditional Chinese medicine and incorporates aspects of meditation and mindfulness training. Cooperation between the body and the mind is emphasized in facilitating and achieving a meditative state (1, 3). Combined use of body and mind training is consistent with studies in which changes in the body influence and facilitate emotional and cognitive processing (4–7). Relaxation training, on the other hand, requires voluntary control in progressive relaxation of the muscles of the body, sending feedback to influence the mind (8, 9). During relaxation training, thinking about control operations could interfere with training effects (1, 3), leading to different results between the IBMT and the relaxation groups.

To test the mechanisms of training, this study used random assignment of 86 Chinese undergraduates to 2 experimental (IBMT) or control (relaxation) groups. Forty-six subjects participated in experiment I using brain imaging and physiological measures, whereas another 40 subjects participated in experiment II using EEG and physiological measures. The physiolog-ical measures included heart rate, skin conductance response (SCR), and respiratory amplitude and rate, to monitor autonomic nervous system activity. These measures allowed evaluation of the training stages in the 2 parallel experiments to make sure all subjects attained similar meditative or relaxation states during and after training.

This design allowed us to apply random assignment using participants without any previous meditation or relaxation experience, given the same amount of training to detect the relationship between the brain networks and the autonomic nervous system (ANS) during training (see *Materials and Methods*).

A brain network including anterior cingulate cortex (ACC) and prefrontal cortex (PFC) has been shown to be an important mechanism for self-regulation of cognition and emotion (10–13). The sensitivity of the ACC to both reward and pain (14, 15) and evidence for ACC coupling to cognitive and emotional areas during task performance (16, 17) support the idea that the role of this brain region is to regulate the processing of information from other networks. The ACC thus serves as part of an executive attention network involved in the control of both cognition and emotion (18). Because the IBMT group showed higher levels of self-regulation than the relaxation group following training (1, 2), we hypothesized that activity in the ACC will be increased more by IBMT than by relaxation training.

Meditation is accompanied by physiological changes. Wallace (19) first reported that transcendental meditation induced physiological changes in oxygen consumption, heart rate, skin resistance, and certain EEG frequencies. Indexes of ANS function including heart rate/heart rate variability (HRV), skin conductance/resistance response, respiratory amplitude/rate, and EEG frequencies have become biomarkers for monitoring meditative states (20–23). Because IBMT changes the state of the body through autonomic control (2, 3), we hypothesized that signs of ANS activity, especially parasympathetic activity, will increase during and following IBMT.

During meditation, an increase in frontal midline theta power as measured from scalp electrodes has been widely reported (20, 24–26). Functional (f)MRI studies have also identified dorsal and ventral ACC involvement in autonomic control (27–30). High-frequency HRV is associated with the parasympathetic component of the ANS and ventral (v)ACC activation correlated significantly with high-frequency HRV, suggesting ACC control of parasympathetic autonomic activity (25, 26, 29). On the basis of these findings, we hypothesized that the IBMT group would show greater EEG power in the frontal midline theta wave (ACC source) and the frontal midline theta rhythm will be positively correlated with high-frequency HRV.

NEUROSCIENCE

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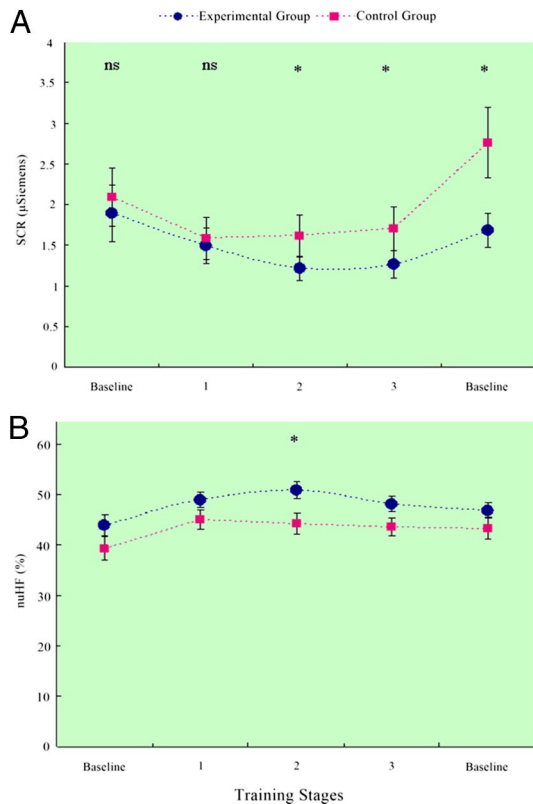
Fig. 1. Physiological indexes comparison for IBMT and relaxation training (RT). (*A*) Skin conductance response (SCR) before, during, and after training in the experimental (IBMT) and control (RT) groups. For SCR, the lower score shows more parasympathetic activity. (*B*) High-frequency HRV before, during, and after training in the experimental (IBMT) and control (RT) groups. For high-frequency HRV, the higher score shows more parasympathetic activity. (*A* and *B*) The horizontal axis indicates the 5 training stages: baseline before training, 3 periods of IBMT or RT with 9 min each (1, 2, 3), and baseline after training. The vertical axis indicates SCR change and percentage of change in normalized units of high-frequency (nuHF) HRV, respectively. *, $P < 0.05$; ns, no significance.

Results

Repeated ANOVAs were conducted with group (IBMT and relaxation) and training session (before, during, and after) as factors. Before training, no differences were found for SCR, heart rate, respiratory amplitude and rate, EEG power, and brain activity between the 2 groups ($P > 0.05$).

Experiment I Physiological Indexes. After 5 days of training, the main effect of training session was significant for SCR in the IBMT group in comparison with the relaxation group [$F (1, 41) = 9.937; P < 0.01$]. The group × session interaction was significant [$F (1, 41) = 6.652; P < 0.01$]. Further, in comparison with relaxation, SCR was significantly lower during practice periods 2 and 3 and after baseline (but not during period 1 and before baseline), indicating that the SCR was related to the amount of training (see Fig. 1*A*).

Similar results were found for heart rate, belly respiratory amplitude, and chest respiratory rate. After 5 days of training, the main effect of training session was significantly lower for heart rate [$F (1, 41) = 27.683; P < 0.01$], greater for belly respiratory amplitude [$F (1, 41) = 12.646; P < 0.01$], and lower for chest respiratory rate [$F (1, 41) = 6.718; P < 0.01$] in the IBMT group compared to the relaxation group. The group × session interaction was significant for heart rate [$F (1, 41) = 10.124; P < 0.01$], belly respiratory amplitude [$F (1, 41) = 10.807;$
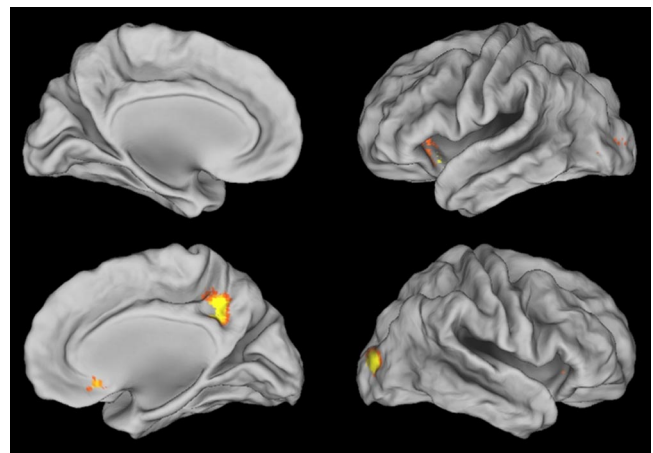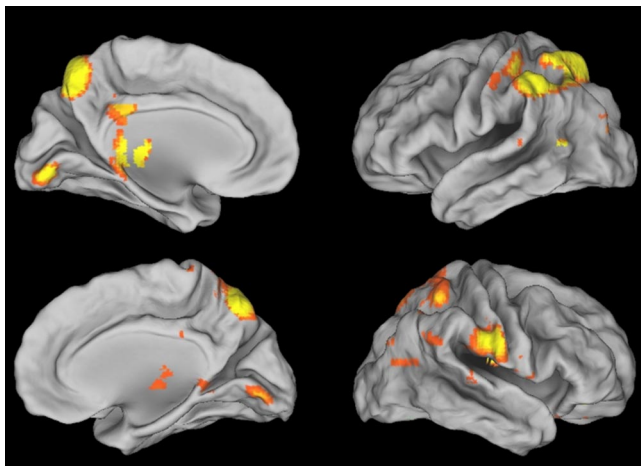

Fig. 2. Comparison maps of r-CBF change in IBMT compared to RT in left and right hemispheres after training minus before training. The upper row is the left hemisphere and the lower row the right hemisphere. Left, a medial view; right, a lateral view (displayed at $P_{FWE} < 0.05$, corrected).

$P < 0.01$], and chest respiratory rate [$F (1, 41) = 13.139; P < 0.01$], respectively.

After 5 days of training, we also performed an analysis of HRV. The main effect of training session was significant for percentage of change in the normalized unit of high-frequency (nuHF) HRV in the IBMT group in comparison with the relaxation group [$F (1, 41) = 21.041; P < 0.01$] and the group × session interaction was also significant [$F (1, 41) = 5.272; P < 0.01$]. In comparison with the relaxation group, high-frequency HRV in the IBMT group was significantly improved during practice period 2 [$F (1, 41) = 6.635; P < 0.05$] and marginally significant during practice period 3 [$F (1, 41) = 3.910; P = 0.055$], respectively, indicating that high-frequency HRV was more related to the state the subjects maintained (see Fig. 1*B*). Results of lower SCR, increased belly respiratory amplitude, decreased chest respiratory rate, and more high-frequency HRV demonstrated the better ANS regulation, especially more parasympathetic activity during and following IBMT in comparison with relaxation.

Experiments I and II Brain Imaging. To explore brain mechanisms during short-term meditation, we recorded brain activity using EEG and single photon emission computed tomography (SPECT) (to avoid fMRI noise that could distract from the meditative state) to get temporal and spatial information (31–33). In experiment I, before training, none of the scalp electrodes of the EEG showed differences between the 2 groups ($P > 0.05$). In the IBMT group, ANOVAs revealed a group × session effect for frontal midline electrodes Fz [$F (1, 32) = 4.921; P < 0.05$], FCz [$F (1, 32) = 4.468, P < 0.05$], and Cz [$F (1, 32) = 5.054, P < 0.05$], respectively. After training, a *t* test indicated significant increases in the IBMT group (but not the relaxation group) in EEG power in the theta frequency band (3–8 Hz) for frontal midline electrodes Fz, FCz, and Cz ($P < 0.05$), often related to generators in the ACC (18, 20, 24, 25).

In experiment II, after 5 days of training, in comparison with the relaxation group, global brain activity was reduced in the IBMT group. However, the IBMT group showed more regional cerebral blood flow (r-CBF) in the right ACC, including the subgenual ACC (Brodmann area, BA 25, $x = 8, y = 18, z = -10$) and adjacent ventral ACC (BA 32), the left insula, the occipital lobule, the right posterior cingulate cortex (PCC), the right precuneus, and subcortical structures of the putamen and caudate ($P_{FWE} < 0.05$, corrected, see Fig. 2).

Fig. 3. Comparison maps of r-CBF change in RT compared to IBMT in left and right hemisphere after training minus before training. The upper row is the left hemisphere and the lower row the right hemisphere. Left, a medial view; right, a lateral view (displayed at $P_{FWE} < 0.05$, corrected).

In comparison with the IBMT group, the relaxation group showed greater r-CBF change in the right frontal lobule (BA 47), the right insula, the temporal lobule (Wernicke's area), the occipital lobule, the parietal lobule, the angular gyrus, the supramarginal gyrus, the lingual gyrus, PCC, the precuneus, and the thalamus ($P_{FWE} < 0.05$, corrected, see Fig. 3).

Experiment II Central and Autonomic Nervous System Interaction. To explore the relationship between brain activity and physiological indexes, we analyzed the correlation between the changes in frontal midline theta power (electrodes Fz, FCz, and Cz, source at the ACC) and high-frequency HRV. After 5 days of the IBMT, correlations between Fz-theta and high-frequency HRV ($r = 0.566$, $P = 0.028$), FCz-theta and high-frequency HRV ($r = 0.551$, $P = 0.033$), and Cz-theta and high-frequency HRV ($r = 0.575$, $P = 0.025$) were significantly positive. However, after 5 days of training for the relaxation group, there was no significant correlation between theta activity and high-frequency HRV (see Fig. 4). While only the IBMT training produced significant correlations, there were no significant differences between correlations for the 2 groups, presumably because the power was too low.

Discussion

Physiology. Physiological measures of heart rate, SCR, respiratory amplitude and rate, and HRV are biomarkers of autonomic regulation in relaxation and meditation (19–23, 34, 35). During and after 5 days of training, both IBMT and relaxation groups
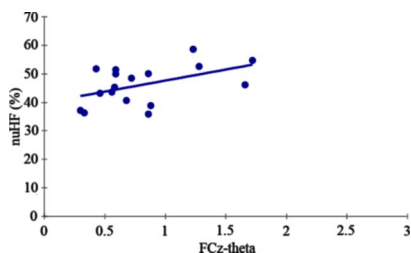
Fig. 4. Correlation between high-frequency HRV and FCz-theta in IBMT following 5 days of training. The horizontal axis indicates the percentage of change in frontal midline theta power (in FCz) and the vertical axis indicates the percentage of change in normalized units of high-frequency (nuHF) HRV. A positive Pearson's correlation was observed ($r = 0.551$, $P = 0.033$).

showed positive changes in physiological indexes, indicating training effects. However, the IBMT group showed significantly better physiological reactions in lower heart rate and SCR, increased belly respiratory amplitude, and decreased chest respiratory rate than the relaxation control. These results reflected ANS regulation with less effort, more relaxation of the body, and a calm state of mind during and after IBMT practice as compared to relaxation training (1–3, 21, 27, 34, 35).

HRV is a noninvasive technique that allows for a reliable and accurate measure of sympathetic and parasympathetic functions. High-frequency HRV is related to parasympathetic function (25, 26, 29, 36, 37). The significant increase of high-frequency HRV in the IBMT group during training indicates successful inhibition of sympathetic tone and activation of parasympathetic tone in comparison with relaxation training. This result was consistent with previous findings of decreased sympathetic activity and increased parasympathetic activity during meditation (25, 26, 29, 38, 39).

Brain Imaging. After 5 days of training, the IBMT group showed more r-CBF change in the right subgenual ACC (BA 25) and adjacent ventral ACC (BA 32) compared to the relaxation group. These brain areas have been related to emotion regulation partly through control of the autonomic system and may implicate the ACC's regulatory role in meditation training (2, 3, 11, 20, 27, 40–47).

Functionally and anatomically, the subgenual ACC is more strongly linked to autonomic control centers than the dorsal (d)ACC (48–50). Whereas the dACC activates during effortful tasks, the subgenual ACC deactivates during attention-demanding tasks and is more active during baseline resting states (51, 52). In our study, the IBMT group showed increased subgenual ACC activity and concurrent high-frequency HRV, one of the parasympathetic indexes of the ANS (25, 26). These observations suggest that subgenual ACC activity relates to parasympathetic, rather than the sympathetic, autonomic system (48, 53). Taken together, greater subgenual ACC (BA 25) and adjacent vACC (BA 32) activity may play an increased regulatory role during and after short-term IBMT.

In contrast, relaxation training produced more frontal, temporal, and parietal cortex activations (including Wernicke's area) than IBMT. Physiological results and self-reports indicated the achievement of relaxation. We did not find more ACC activity following relaxation training, however. Instead, the right ventral lateral PFC (BA 47) was more active, and this area is well known as a region critical for cognitive control, response inhibition, and the selection of information (47, 54). The reason for the high level of brain activation in the relaxation group may derive from the "doing state" requiring paying attention and using effortful control to relax different body parts during the training session (see Fig. 3). These differences between IBMT and relaxation may imply different regulatory strategies during relaxation training, such as conscious control by the use of language, attention, etc. The activation patterns shown by the relaxation group are in line with the control of goal-directed and stimulus-driven attention in the brain, indicating that effort and control are needed to maintain the relaxation state (52, 54–59).

In our study we also detected more activity of the putamen and the caudate in the IBMT group, which may indicate involvement of executive function and reward systems during meditation (60, 61). The reward-related activity during and after IBMT practice may help the practitioner maintain a positive mood (1, 3), triggering neuromodulators associated with reward such as dopamine (62), to maintain a longer meditative state (2).

The brain default network is characterized by activity in midline areas within the medial PFC, the PCC, and the precuneus (51). Activity in these regions is related to spontaneous self-generated mental activity, i.e., streams of thoughts, episodic

memories, and wandering minds (56, 63, 64). Both IBMT and relaxation groups showed different brain patterns in this default network, indicating that training could affect the resting states (65, 66). In comparison with the relaxation control, the IBMT group showed a marked global reduction of activation, including the default network after training, further suggesting effective change and reorganization of the brain networks. This reduced brain pattern may reflect less effortful mental processes during IBMT practice. This may involve using minimal control to maintain the internal state of "being" rather than the state of "doing" used in relaxation training. This proposal was supported by evidence from self-reports of "forgetting my body or myself" in the IBMT group.

Greater precuneus and PCC activation in the relaxation group than in the IBMT group may indicate more self-referential awareness and thoughts (54, 67, 68). These are in line with previous findings that PCC activation is related to the mental self (69), and the precuneus involves self-centered mental imagery strategies and an episodic memory retrieval (70) and adaptive control network (54). How training changes the default network and reallocates the brain resources will require further investigation.

Central and Autonomic Nervous System Interaction. Increased EEG frontal midline theta power has been widely reported during meditation, and the ACC is suggested to be the generator of this activity (20, 24–26). After 5 days of training, the IBMT group (not the relaxation group) showed significant increases of theta power in frontal midline electrodes Fz, FCz, and Cz (ACC source). The frontal midline theta rhythm was associated with the parasympathetic component of the ANS (24, 26, 29). In combination with greater parasympathetic activity in lower heart rate and SCR, increased belly respiratory amplitude, decreased chest respiratory rate, and high-frequency HRV, these results provided strong evidence of central and autonomic nervous system interaction in IBMT practice. Skinner (71) reported brain control of cardiovascular dynamics. fMRI studies have found dACC and vACC involvement in autonomic control, and vACC activation correlated significantly with high-frequency HRV (27–30). These results suggest ACC control of parasympathetic autonomic activity (29, 30). Our results are consistent with previous studies indicating increased parasympathetic activity following meditation (25, 26).

After 5 days of training, the IBMT group also showed more left insula activity when compared with the relaxation group. Whereas Oppenheimer et al. (72, 73) reported the left insula is predominantly responsible for parasympathetic effects, this activation could reflect increased parasympathetic activity. We also found a significant correlation between high-frequency HRV and frontal midline theta activity only for the IBMT group (source at ACC). The significant increase in the correlation between frontal-midline theta and high-frequency HRV in the IBMT group is consistent with this idea. These changes indicated increased central and autonomic nervous system interaction that may be a result of the brain–body harmony emphasized in the practice of IBMT (3, 30). The concurrent increase in activation in the subgenual ACC and left insula in the IBMT group was consistent with previous findings of the distribution of Von Economo neurons (74, 75) in these 2 brain areas and their connectivity in the resting state (56). These 2 regions may provide an anatomical base for successful self-regulation.

We also found more activation of the right insula than the left insula in relaxation training. The right insula has been proposed to play a role in attending to internal bodily states (interoceptive awareness) and to be involved in energy expenditure and arousal (76–78). Several meditation studies have reported right insula involvement including focused attention to internal experiences (58), observation of the ongoing stream of internal experiences (79), and momentary self-reference centered on the present

(65). These forms of meditation training usually require concentration and effort to maintain the state (48, 65, 78, 80), and this effort is consistent with the function of the right insular cortex, which is more likely to produce sympathetic responses (72, 73). The finding that right insula activity is related to the regulation strategies of conscious control is congruent with its occurrence in relaxation and in some forms of meditation. Our results suggest that while many forms of meditation should produce stronger ACC activity, the forms that emphasize control of the mind might show more dorsal activation and would be more likely to produce sympathetic activity.

Model. Both brain imaging and physiological measures indicated that the IBMT group demonstrated changes in the autonomic and central nervous system that seemed to reflect the instruction to achieve equilibrium between body and mind (2, 3). Five days of IBMT improves attention and self-regulation by changing the interaction between the central (brain) and the autonomic (body) systems as indexed by ACC theta power and high-frequency HRV correlation. We believe that IBMT works by facilitating the achievement of a balanced body–mind state, producing the changes in brain and autonomic activity and their interaction observed in this study.

Materials and Methods

Participants. Eighty-six healthy Chinese undergraduates at Dalian University of Technology [42 males, mean age ($\pm$ SD) = 21.45 $\pm$ 2.22] without any training experience were randomly assigned to 2 experimental (IBMT) or control (relaxation) groups for experiment I and experiment II. Forty-six subjects participated in experiment I, using brain imaging and physiological measures, whereas another 40 subjects participated in experiment II, using EEG and physiological measures. All were free of cardiac, respiratory, and other diseases that would cause ANS dysfunction. No subject was medicated and no subject was a smoker or a habitual drinker. The experimental groups continuously attended IBMT for 5 days of training, 20 min per day. The control groups were given the same amount of muscle relaxation training sessions (see ref. 1 for details). Each person filled out a daily self-report questionnaire after each session and recorded day-to-day experiences before and after 5 days of training. The human experiment was approved by the local Institutional Review Board, and informed consent was obtained from each participant.

Experiments I and II Physiological Measures. To monitor real-time ANS activity and attain steady physiological signals during the training stage, we divided the training into 5 periods and recorded baseline before training, three 9-min periods of IBMT or relaxation (labeled as 1, 2, and 3 in Fig. 1), and baseline after training in 2 parallel groups to make sure all subjects attain similar meditation or relaxation states during and after training (1, 2).

To quantify the alteration in ANS function before, during, and after practice, heart rate, SCR, belly respiratory amplitude, and chest respiratory rate were recorded for each subject in 5 periods (19, 21, 23, 81). The physiological data were recorded and analyzed in 8 channels of the Procomp Infiniti System from Thought Technology. Power spectral analysis of HRV was performed with a fast Fourier transform and Biograph software, and spectral components were identified and then assigned, on the basis of their frequency: high frequency (HF; 0.16–0.45 Hz), low frequency (0.04–0.15 Hz), and very low frequency (VLF; 0−0.03 Hz). These components were obtained in absolute values of power (ms^2). HF components are reported in normalized units (nuHF), representing the relative value of the power of each component in proportion to the total power minus the VLF component (25, 26, 82). We report physiological data from experiment I in which 43 participants (20 in the IBMT group) had usable data after movement artifacts were eliminated. To control for variations of physiological indexes over the circadian rhythm, the measurements were performed from 2 p.m. to 6 p.m.

Brain Imaging. *Experiment I SPECT.* Neuroimaging data were acquired on a GE SPECT scanner (Millenium VG, GE Healthcare). Subjects were instructed to rest in the room with their eyes closed and ears unoccluded for 10 min at which time they were injected with 25 mCi of ^{99m}Tc-ECD. Twenty minutes following the injection, the subject was scanned for 30 min in a dual-headed rotating gamma camera using low-energy high-resolution collimators (VP 45). Each subject received 2 scans before and after 5 days of training. Forty subjects (20 in each group) had usable imaging data after motion correction, which were

analyzed using Statistical Parametric Mapping (www.fil.ion.ucl.ac.uk/spm/). Images for each participant were realigned to correct for head motion, normalized into a standard stereotactic space as defined by the Montreal Neurological Institute (MNI), and smoothed with an 8-mm Gaussian kernel, full width at half maximum (2, 32, 33, 83).

The voxelwise threshold for activation was set at $P_{FWE} < 0.05$, corrected for the number of resolution elements in each of the regions of interest (ROI) by using the SPM small volume correction (SVC) procedure together with brain masks defined by the automated anatomical labeling toolbox (AAL) (www.fil.ion.ucl.ac.uk/spm/ext). The brain masks defined the brain regions over each of which the SVC was performed. These brain regions included subgenual ACC (BA 25), frontal lobule (BA 47), insula, temporal lobule (Wernicke's area), occipital lobule, parietal lobule, angular gyrus (BA 39), supramarginal gyrus, lingual gyrus, PCC, precuneus, putamen, caudate, and thalamus. The global pattern of the r-CBF changes in these areas was illustrated using caret software (see Figs. 2 and 3).

With the advance of new high-resolution collimators, SPECT has been improved in spatial resolution and is widely used in clinics and research to locate ACC and subcortical regions (32, 33, 83). In addition, our recent IBMT studies using a 3T Siemens fMRI scanner provide consistent results of subgeneul and ventral ACC activation after 5 days of IBMT (2).

Experiment II EEG. EEG activity was recorded by using the Brain Products System (BP) and analyzed by Brain Vision Analyzer software 1.05, with 19 Ag/AgCl electrodes following the International 10–20 System: FP1, FP2, Fz, F3, F4, F7, F8, Cz, C3, C4, Pz, P3, P4, T3, T4, T7, T8, O1, and O2 (24, 80). The EEG signal was digitized at 500 Hz. The impedance of each electrode was <5 k. An electrode placed on the vertex (FCz) served as a reference with an analog pass band of 0.01–100 Hz. EEG data were filtered with low-pass filters at 0.5 Hz and high-pass filters at 45 Hz, rereferenced to the average reference. Thirty-four subjects (17 in each group) had usable data after artifact rejection, and these data were further analyzed using Pearson's correlation between percentage of change in frontal midline theta power (electrodes Fz, FCz, and Cz) and percentage of change in high-frequency HRV in the same group. Artifact-free EEG segments were selected for each condition of 5 min of baseline (eyes closed) before and after training and 20 min of training, and then were fast Fourier transformed (FFT) and averaged in the frequency domain. The delta (1–3 Hz), theta (3–8 Hz), alpha (8–12 Hz), beta (12–32 Hz), and gamma (33–45 Hz) frequency bands were analyzed (2, 25, 26, 82).

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