Distribution of Cerebral Blood Flow during Biofeedback Training

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(Received December 27, 2013; Accepted January 10, 2014)

Near-infrared spectroscopy (NIRS) is less restrictive for examinees than other brain function imaging methods such as positron emission tomography or functional magnetic resonance imaging. In addition, fixation of the head and recumbence on a special device during measurement are unnecessary with NIRS. Biofeedback training (BFT) elucidates the importance of mental training, and monitors and encourages the learning of psycho-physiological control necessary for peak performance. Electromyography of examinees' rectus femoris muscles and near-infrared spectroscopy were simultaneously conducted to investigate the relationship between BFT and local cerebral blood flow. The influence of a kicking motion on brain functioning was confirmed. These findings suggest that BFT is effective in activating working memory.

Key words: Biofeedback Training (BFT), Kicking Motion, Cerebral Blood Flow, Near-infrared Spectroscopy (NIRS)

1. Effect of Biofeedback Training on Human Brain Activity

Biofeedback is a means for gaining control of bodily processes to increase relaxation, relieve pain, and improve health, among other benefits. A biofeedback instrument has three tasks (Peek, 1995):

- To monitor (in some way) a physiological process of interest.
- To measure (quantify) what is monitored.
- To present what is monitored or measured as meaningful information.

The contributions of many previous researchers and practitioners can be cited as forerunners of biofeedback training.

Electromyography (EMG) and biofeedback are often used simultaneously to handle movement during a procedure. Edmund Jacobsen commenced his research at Harvard in 1908 and worked throughout the 1920s and 1930s to develop progressive muscle relaxation as an effective behavioral technique for the alleviation of neurotic tensions and many functional medical disorders (Jacobson, 1938). He used crude EMG equipment to monitor the muscle tension levels in his patients during the course of treatment. The classification of and historical perspectives on biofeedback applications have been published in the following studies: Gatchel and Price (1979), Gaarder and Montgomery (1981) and Basmajian (1989).

Biofeedback training (BFT) is not only investigated with regard to its involvement in health promotion, but it is also attracting attention as a factor influencing the development and maintenance of brain function (Nanhoe-Mahabier *et al.*, 2012; Calomeni *et al.*, 2013). The relationship between BFT and brain functioning is attracting increased attention. Reportedly, BFT is not a mere voluntary movement to move the leg and genicula, but is also involved in advanced integrative functions of the brain.

With the recent development of noninvasive brain activity measurement techniques, such as near-infrared spectroscopy (NIRS), and smaller medical devices, brain science has rapidly developed and various brain dynamics have been uncovered.

In this study, to clarify the influence BFT has on the brain, young males were asked to perform BFT and NIRS simultaneously, and the relationship between BFT and the distribution of cerebral blood flow was investigated.

2. Near-infrared Spectrum (NIRSpec)

NIRS is less restrictive for examinees than other brain function imaging methods such as positron emission tomography and functional magnetic resonance imaging. In addition, fixation of the head and recumbence on a special device during measurement are unnecessary with NIRS (Villringer and Dirnagl, 1995; Villringer and Chance, 1997; Okamoto *et al.*, 2004). However, measured NIRS values represent relative changes in the concentration of blood hemoglobin, not absolute values; the length of the optical path from irradiation through detection cannot be measured.

When a brain region is active, blood flow increases in the region. Thus, the activity of cerebral regions can be estimated by measuring changes in cerebral blood flow. In NIRSpec, blood flow is determined by measuring hemoglobin-carrying oxygen consumed by cell activity.

With NIRS, the cerebral cortex activity is measured by employing multichannel reflected light measurements on

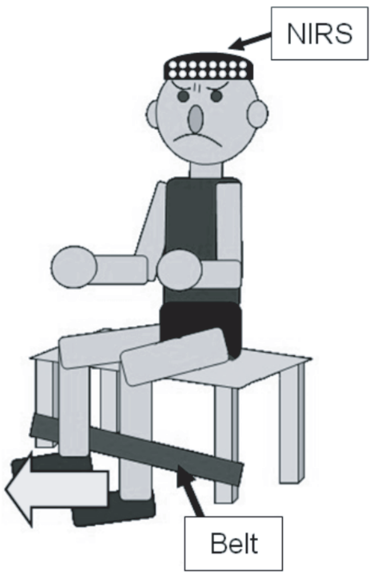

Fig. 1. BFT of rectus femoris muscles.

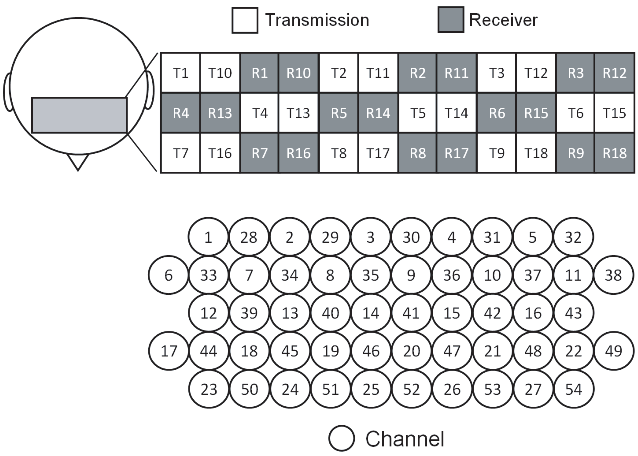

Fig. 2. Arrangement of channels between transmission and receiver probes.

the scalp. In this method, light transmission and receiver probes are attached to the scalp. Near infra-red at approximately 700–1000 nm has high penetrability of biological tissues and is irradiated from the light transmission probe. Scattered and reflected light on the cerebral cortex surface are detected via the light receiver probe.

There are two types of blood hemoglobin: oxygen-bound oxidized hemoglobin (Oxy-Hb) and oxygen-unbound deoxidized hemoglobin (Deoxy-Hb), and the absorbance wavelength characteristics for each of these types are different. By utilizing these properties, blood flow is calculated from the attenuation level of detected light.

In NIRSpec, Oxy-Hb, Deoxy-Hb, and the total hemoglobin levels (Total-Hb) in the cerebral cortex are estimated from detected light (Villringer and Dirnagl, 1995; Villringer and Chance, 1997). Because changes in each hemoglobin level measured by NIRS are relative to the baseline level at the measurement's initiation, and the length

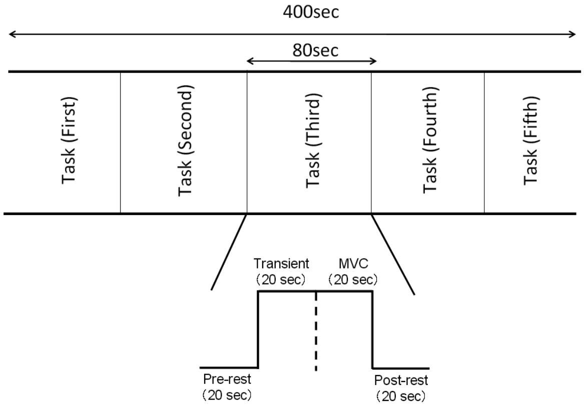

Fig. 3. Experimental protocol.

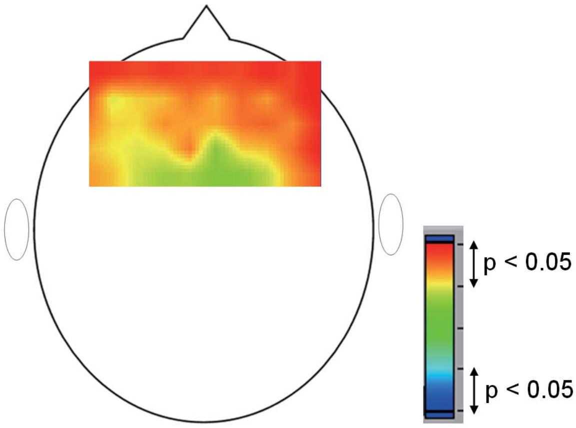

Fig. 4. Significant increase in Oxy-Hb was observed during the BFT task in warm color areas.

of the optical path of the near-infrared laser light varies depending on the physical characteristics of the subjects, it is difficult to simply compare the measured value among the subjects and calculate the mean.

3. Simultaneous Measurement of NIRSpec

We performed the following experiment to provide an example of the influence masticatory movement has on the brain. Using NIRSpec, BFT muscle activity and local cerebral blood flow were simultaneously measured. The influence of BFT on brain activity was evaluated.

The subject was a healthy 22-year-old male with no impediments to normal leg functioning, such as pain in the knee joint, calves, or rectus femoris muscles. The cerebral blood flow was recorded while BFT was performed. The experiment was fully explained to the subject beforehand, and written consent was obtained.

He performed BFT for 6 min 40 s (400 s). We ensured that experiment was not as a result of the environmental conditions; using an air conditioner, we adjusted the temperature to 25°C in the exercise room, which was large, quiet, and bright.

The subject sat back on a four-legged stool, and electromyographic electrodes located at intervals of several centimeters were applied to the venter of the rectus femoris muscle in the dominant left or right leg (Fig. 1). The subject was instructed to kick a fixed belt with the bottom of the lower leg (kicking motion).

Changes in the blood oxygenized hemoglobin levels in the brain were measured using the near-infrared light brain function imaging system, LABNIRS (Shimadzu Corporation), at a sampling frequency of 17.5 Hz. A fiber holder was attached to the subject's head, and light transmission/receiver probes were attached as shown in Fig. 2. Cerebral blood flow on the frontal lobe, occipital lobe, and parietal lobe were measured at 54 channels (Fig. 2).

The experiment was performed in a sitting position. The following protocol was repeated five times: 20-s pre-rest, 40-s kicking motion (first half of 20 s was transient, last half of 20 s was performed with maximum voluntary contraction), followed by 20 s of rest (Fig. 3). Brain activity was measured using NIRS while confirming the BFT. Monitoring changes in Oxy-Hb. The statistical evaluation was based on a least-squares estimation using the general linear model (GLM) for serially autocorrelated observations (Friston, 1994; Friston *et al.*, 1995a, 1995b, 2000, 2006; Worsley and Friston, 1995). The design matrix was generated with a box-car function. The model equation, including the convolved with Gaussian kernel of dispersion of 4 s full-width half-maximum. In addition, we compared changes in levels of Oxy-Hb at rest and during the task at each channel by employing one-way analysis of variance (ANOVA). The states (rest or task) was the factor of the statistical analysis. In accordance with Bonferroni's method, the post-hoc test was held at each channel with significance level 0.05. A small value p-value ($p < 0.05$) indicates strong evidence against the null hypothesis; there is no statistical difference between rest and task states. Areas marked by using cool and warm color mean specific decrease and increase in Oxy-Hb during the task, respectively (Fig. 4).

Regarding the one-way ANOVA of the hemoglobin levels at rest and during the task, a primary effect was noted for the factor ($p < 0.05$). Therefore, the cerebral blood flow did not uniformly change, but rather locally increased or decreased.

The differences between Oxy-Hb averaged during rest and during the task were calculated at each channel and interpolated using the spline method. As shown in the brain mapping (Fig. 4), significant differences between Oxy-Hb at rest and Oxy-Hb during the task were obtained using the post-hoc test ($p < 0.05$). As a result, the cerebral blood flow on the frontal lobe increased during BFT. In addition, the cerebral blood flow on the primary motor cortex and parietal association area of the parietal lobe increased during BFT. The symptoms of dementia and fatigue often involve weakened regulation of working memory, emotion, and behavior, which are controlled by the prefrontal cortex. Therefore, these results suggest that BFT is effective for activating working memories. BFT may help in the treatment of memory loss caused by dementia and may enhance learning effects.

To clarify the influence BFT movement has on the brain, young males performed BFT and NIRS simultaneously to investigate the relationship between BFT and local cerebral blood flow.

Cerebral blood flow increased with BFT but decreased following BFT and returned to the baseline level prior to BFT. The increased cerebral blood flow indicated that BFT activated the entire prefrontal area. This further suggests that BFT activates the brain, which may be effective for improving working memory and reducing stress.

Effects regarding the differences in BFT rhythm on brain activity will be further studied.

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