

Neural correlates of regional EEG power change

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To clarify the physiological significance of task-related change of the regional electroencephalogram (EEG) rhythm, we quantitatively evaluated the correlation between regional cerebral blood flow (rCBF) and EEG power. Eight subjects underwent H₂¹⁵O positron emission tomography scans simultaneously with EEG recording during the following tasks: rest condition with eyes closed and open, self-paced movements of the right and left thumb and right ankle. EEG signals were recorded from the occipital and bilateral sensorimotor areas. Cortical activation associated with EEG rhythm generation was studied by the correlation between rCBF and EEG power. There were significant negative correlations between the sensorimotor EEG rhythm at 10–20 Hz on each side and the ipsilateral sensorimotor rCBF and between the occipital EEG rhythm at 10–20 Hz and the occipital rCBF. The occipital EEG rhythm showed a positive correlation with the bilateral medial prefrontal rCBF, while the right sensorimotor EEG rhythm showed a positive correlation with the left prefrontal rCBF. In conclusion, decrease in the regional EEG rhythm at 10–20 Hz might represent the neuronal activation of the cortex underlying the electrodes, at least for the visual and sensorimotor areas. The neural network including the prefrontal cortex could play an important role to generate the EEG rhythm.

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Abbreviations: ANCOVA, analysis of covariance; EEG, electroencephalogram; EMG, electromyogram; EOG, electro-oculogram; ERD, event-related desynchronization; ERS, event-related synchronization; FWHM, full width at half-maximum; M1, primary motor cortex; PET, positron emission tomography; rCBF, regional cerebral blood flow; S1, primary sensory cortex; SM1, primary sensorimotor cortex; SPM, statistical parametric map.

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Introduction

The electroencephalogram (EEG) represents the summed postsynaptic potentials of cortical neurons (Niedermeyer and Lopes da Silva, 1987). The generator mechanisms of EEG rhythm in various frequency bands, however, are not well understood.

In normal subjects, the EEG rhythm at 8–12 Hz is usually most conspicuous over the parieto-occipital area (Berger, 1929; Pfurtscheller and Lopes da Silva, 1999) and is called the occipital alpha band rhythm. The EEG alpha band rhythm may be associated with the alert and yet relaxed state and is commonly used as an indirect measure of the functional organization of brain. It is well known that normal awake alpha band rhythms are ‘blocked’ (substantially reduced in amplitude) by eye opening and moderate to difficult mental tasks (Berger, 1930, 1932; Nunez et al., 2001; Vijn et al., 1991). Thus, some authors suggested that the occipital alpha band rhythm might be considered as an idling rhythm of visual areas (Kuhlman, 1978).

One of the most relevant activities overlapping the occipital alpha band rhythm is the so-called mu rhythm which is restricted over the hand area of the primary sensorimotor cortex (SM1) and is suppressed not by eye opening but by active hand movements. The sensorimotor mu rhythm could also be considered as an idling rhythm of sensorimotor areas (Kuhlman, 1978; Pfurtscheller, 1992). Although the role of the thalamocortical circuitry in the generation of sleep spindles has been emphasized (Steriade et al., 1990), the neurophysiological mechanisms by which the regional alpha band rhythm such as the occipital alpha or the sensorimotor mu rhythm are to be generated or suppressed are still unclear.

Higher frequency EEG waves such as the beta band rhythm (13–30 Hz) are associated with the cortical activation most pronounced during the awake state and rapid eye movement sleep (Nofzinger et al., 2000). During various motor tasks, EEG studies showed a transient decrease of EEG power in the beta band (Pfurtscheller, 1989), which is called event-related desynchronization (ERD) (Pfurtscheller, 1977; Pfurtscheller and Aranibar, 1977)

or task-related power decrease (Gerloff et al., 1998). This decrease starts 1–2 s prior to the movement onset and is followed by a rebound-like increase just after termination of the movement (event-related synchronization: ERS) (Pfurtscheller, 1992). It is speculated that the motor cortex shifts from an activated state during preparation and execution of movement (working cortex) to a resting state after termination of movement or, in other words, from a processing mode to an ‘idling’ mode (Pfurtscheller et al., 1996). This hypothesis is also supported by a transcranial magnetic stimulation study showing decreased corticospinal excitability at the time of the 20-Hz event-related synchronization (Chen et al., 1998). However, the generator mechanism of regional beta band rhythm is still unknown.

Brain electrical activity represents the single greatest demand on cerebral metabolism (Erecinska and Silver, 1989), suggesting that measurement of electrical energy also should be coupled to cerebral metabolism and perfusion. In normal subjects, cerebral glucose uptake and blood flow are generally accepted as tightly coupled measures of cerebral energy utilization (Sokoloff, 1977, 1981). The association between EEG power and cerebral glucose metabolism has been occasionally studied using the 18-fluoro-deoxyglucose positron emission tomography (PET) technique (Larson et al., 1998; Oakes et al., 2004; Schreckenberger et al., 2004). However, a limitation of the 18-fluoro-deoxyglucose tracer is that over the span of 30 min it is difficult to ensure that the subject remains in the same functional state (Oakes et al., 2004). Regional cerebral blood flow (rCBF) has been used as an indirect measure of functional neural activity (Raichle, 1987) and the PET technique is considered to be the ‘gold standard’ in CBF measurements in humans (Feng et al., 2004). Measurement of rCBF using $H_2^{15}O$ PET has been well established based on the single-tissue compartment model for diffusible tracers in at least physiologically normal brain tissue (Sadato et al., 1998). The $H_2^{15}O$ tracer has shorter time frame (10–30 s) than the 18-fluoro-deoxyglucose tracer (20–30 min) and the results of $H_2^{15}O$ PET examinations directly depend on the acute cerebral state of activation during tracer injection (Schreckenberger et al., 2004). In normal subjects, cerebral blood flow is generally accepted as tightly coupled measures of cerebral energy utilization (Sokoloff, 1977, 1981). It was reported that EEG power showed strong associations with rCBF in most frequency bands including the alpha and beta range (Leuchter et al., 1999). Therefore, taken together with the EEG power change described above, it is predicted that rCBF associated with the neuronal activation might covary with the EEG power in at least normal subjects. Although previous reports (Ingvar et al., 1976; Paulson and Sharbrough, 1974) mentioned the relationship between EEG and rCBF in humans, the record of EEG and rCBF could not be done simultaneously due to limitations in the EEG and rCBF technique. Recently, the association between EEG power and rCBF recorded simultaneously has been occasionally studied using the $H_2^{15}O$ technique (Leuchter et al., 1999; Nakamura et al., 1999; Sadato et al., 1998). However, the previous reports investigated a correlation between rCBF and the EEG rhythm averaged across the whole scalp. The averaged EEG rhythm might be inappropriate to investigate regional EEG power change such as sensorimotor mu rhythm because the occipital alpha band rhythm may diminish an effect of sensorimotor mu rhythm in the averaged alpha power. Therefore, it would be preferable to investigate the relationship between rCBF change induced by several tasks and the regional EEG rhythm to clarify

neurophysiological mechanisms in the generation or suppression of the regional EEG power. To achieve this goal, we employed rather simple tasks that are commonly used in clinical EEG recording.

The purpose of the present study is to quantitatively evaluate the correlation between rCBF changes using $H_2^{15}O$ PET and EEG power changes induced by several motor tasks and clarify what brain regions are involved in the generation and suppression of the regional EEG rhythms.

Methods

Subjects

Eight right-handed healthy volunteers (5 males and 3 females; mean age \pm SD, 42 \pm 10 years) participated in the experiment. The protocol was approved by the NINDS Institutional Review Board and the NIH Radiation Safety Committee. All subjects gave their written informed consent for the study and had no medical history of neurological or psychiatric disorders.

Tasks

The subjects lay in a supine position and the following tasks were performed twice for each (total 10 times):

1. rest condition with eyes closed (EC)
2. rest condition with eyes open (EO)
3. self-paced right thumb abduction and adduction movement (1–2 Hz) with eyes closed (RH)
4. self-paced left thumb abduction and adduction movement (1–2 Hz) with eyes closed (LH)
5. self-paced right ankle extension and flexion movement (1–2 Hz) with eyes closed (RF)

The order of tasks was randomized across subjects. Electrophysiological recording and PET scanning were carried out simultaneously in all conditions (Fig. 1).

Electrophysiological recording

EEG signals were recorded from 6 electrodes (O1, O2, C3, C4, FC3, FC4 according to the International 10–20 System) secured with collodion and referenced to the right earlobe electrode (A2). The left earlobe electrode (A1) was recorded as a separate channel. To reliably estimate the scalp EEG potential, we converted the EEG signals into the digitally linked earlobe reference before further analysis (Mima and Hallett, 1999; Nunez et al., 1997). A previous study showed that the electrode locations of FC3/C3, FC4/C4 and O1/O2 are just over the left and right SM1 and the occipital cortex, respectively (Steinmetz et al., 1989). Electromyogram (EMG) signals were recorded from 5 muscles (right abductor pollicis brevis [APB], biceps [BIC], left APB, BIC and right hamstring). To monitor the eye movement and blinking, electro-oculograms (EOGs) were monitored by pairs of electrodes placed at the left and right lateral canthus for horizontal eye movement and by another pair of electrodes placed below and above the right eye for vertical eye movement. To monitor tongue movement, a surface electrode placed at the upper edge of the right nasolabial fold

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