이학석사 학위논문

The role of gamma connectivity in the human prefrontal cortex in the Bereitschaftspotential

운동준비전위 동안 인간의 전전두엽에서 나타나는 감마파 연결성의 역할

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Abstract

Objects: The Bereitschaftspotential (BP) is a slow negative cortical potential related to the intention, decision, execution, and control of a movement. The prefrontal cortex (PFC) is known to be one of the generators of BP and to play an important role in cognitive preparation and decision making. Since movement preparation needs the synchronous activity of various neurons, BP may be developed through the exchange of information between motor-related neurons. However, the relationship between BP and information flow is not yet well-known. In the present study, we aim to investigate how the connectivity in the PFC changes during the occurrence of BP.

Method: Electrocorticography (ECoG) was recorded in 5 patients with epilepsy. The subjects performed self-paced hand grasping for 5 minutes during each session, and 3 sessions were recorded for each subject. In the PFC region, electrodes showing prominent BP were selected by visual inspection. An equal number of electrodes distant from the PFC were chosen as a comparison model. We compared the intraregional connectivity between

the PFC and non-PFC regions using partial directed coherence (PDC, range 0-1, 0 denoting no coherence and 1 denoting complete coherence).

Results: In the PFC, the connectivity of beta and gamma bands in the BP period increased by an average of 24.4% compared with the baseline connectivity. Conversely, the gamma connectivity in the non-PFC regions decreased by 31.4%. Moreover, the intraregional connectivity in the PFC increased according to the stage of BP, i.e. baseline (0.24) early (0.30) and late (0.32) periods.

Conclusion: The increased gamma band connectivity in the PFC implies that the increased communication among neurons in the PFC is associated with the development of BP. This finding shows that voluntary movement is developed by intraregional connectivity in the PFC, and reflects the activation of brain networks related to movement preparation.

Key words

Bereitschaftspotential, Readiness potential, electrocorticography (ECoG), connectivity, Partial Directed Coherence (PDC), prefrontal cortex, movement preparation, beta and gamma band.

Contents

1. Introduction

Movement of the human body is more than simply muscle activity, involving higher cognitive function in the planning of when and how to move. For a precise voluntary movement, warm-up time is needed to gather information from environmental sensory signals and internal brain processing. In electroencephalography (EEG), this preparatory activity is shown as a slow and negative potential known as the Bereitshcaftspotential (BP) or the readiness potential (RP) (Kornhuber & Deecke, 1965). BP reflects the intention, planning and execution of a movement, and begins up to 2 seconds prior to the onset of muscle movement (Shibasaki, Barrett, Halliday, & Halliday, 1980). BP has mostly been reported in the motor area (Deecke & Kornhuber, 1978; Neshige, Luders, Friedman, & Shibasaki, 1988; Roland, Larsen, Lassen, & Skinhoj, 1980). However, according to more recent studies, the prefrontal cortex (PFC) is also an important area in the generation of BP (Jahanshahi, Dirnberger, Liasis, Towell, & Boyd, 2001; Jahanshahi *et al.*, 1995; Rektor, Feve, Buser, Bathien, & Lamarche, 1994; Ryun *et al*., 2014).

BP is not formed as a spike but as a gentle slope and is built up slowly compared with other

brain responses such as evoked potentials, due to the fact that a BP may be developed gradually through the accumulation of information from various brain areas. The more information a BP has about the intended movement, the larger the amplitude or latency (Morgan, Wenzl, Lang, Lindinger, & Deecke, 1992). Therefore, the BP for an accurate movement may require sufficient time to receive information from the movement-related areas.

BP consists of two components with different slopes, the early BP developing approximately 1500 ms before the onset of a movement. The late BP that follows the early BP is developed approximately 500 ms prior to a movement, and has a relatively steep slope (Neshige *et al.*, 1988). While the early component is known to be related to the intention and decision process, the late component is known to be related to movement execution and control (Shibasaki & Hallett, 2006). However, there are individual variants of these two BP components, depending on the movement, the late BP can be larger or smaller than the early BP. In addition, the onset latency of the early BP is reported to have a large inter-individual variability (Kukleta, Turak, & Louvel, 2012), implying that a

movement may need different amounts of information depending on the type of movement. Different information processes may result in the inter-individual and inter-conditional variability of the BP. Therefore, BP could be developed to exchange information and to accumulate its connectivity between motor-related neurons for precise and intended movements.

Intraregional connectivity indicates a small network connectivity that shares similar work simultaneously, whereas interregional connectivity is long-range connectivity between different regions cooperating in identical goals such as the sensory-motor network (Dum & Strick, 2005; Passingham, 1993) and the language network (Friederici, 2002, 2012). Planning a movement and deciding the appropriate onset time are needed for participation of movement-related brain regions such as the PFC and the motor cortex. Thus, information flow within the movement-related region may be involved in the decision of diverse movements, and would be reflected in the brain connectivity. This connectivity may underlie the development stage of a BP for a specific movement. Thus, the intraregional connectivity within the movement-related region would be associated with BP

generation.

The present study aims to investigate the role of connectivity in the generation of a BP in the PFC before movement. To do this, we have two hypotheses on the neural basis of a BP. Firstly, a BP is generated by intraregional connectivity in the PFC and an increase in BP is related to an increase in the amount and strength of connectivities. Secondly, there are comparable connectivity differences between the PFC and the non-PFC areas during a BP.

2. Materials and Methods

2.1. Subjects

5 subjects (3 females and 2 males, aged 25-37 years) with intractable epilepsy participated in the present study. All patients underwent implantation of subdural electrodes for clinical purposes. The clinical demography of the patients is presented in Table 1. Computed tomography (CT, Siemens SOMATOM sensation16, Siemens medical solution, Erlangen, Germany) for each subject was carried out before and after the implantations of the subdural electrodes. Magnetic resonance images (MRIs, GE Signa 3T scanner, GE medical system, Milwaukee, Wisconsin) were also acquired after the implantation. Experiments were performed after receiving the patients' written consent, which were approved by the Institutional Review Broad of Seoul National University Hospital (IRB No.H-0912-067-304).

[Table 1 insert here]

2.2. Experimental protocols and data acquisition

The subjects were instructed to perform self-paced hand grasping on the contralateral hand of the implantation hemisphere. They performed the hand grasping in accordance with the instructions that had enough inter-trial intervals more than 5s. The patients were instructed not to count the number of seconds in an interval, and we emphasized the importance of movement intention immediately before performing the movement. Three sessions were recorded for each patient, with each session taking roughly 5 minutes, with a 2 minute rest between sessions.

Patients implanted with electrocorticography (ECoG) which is the practice of using electrodes placed directly on the exposed surface of the brain to record electrical activity from the cerebral cortex. Each patient had 48-88 subdural electrodes (Ad-tech Medical Instrument Co., Racine, WI, U.S.A), with each electrode having a diameter of 4mm with an inter-electrode distance of 10mm. The brain model and implanted electrodes were reconstructed from the individual MRI and CT images using CURRY (version 8.0, Compumedics Neuroscan, U.S.A.). The Electrocorticography (ECoG) was recorded using a digital video EEG monitoring system (Telefactor Beehive Horizon with an AURA® LTM

64 & 128-channel amplifier system, West Warwick, Rhode Island, U.S.A.), digitized at sampling rates of 400 or 1000 Hz and filtered from 0.1 to 100 Hz. The cheek bone was used as a reference. Additionally, electromyography (EMG) was carried out in order to detect the onset of the movement of the opponens pollicis for hand grasping. Electrooculography (EOG) was also carried out in order to simultaneously monitor eye-blinking and eye-movement. The entire experiment was video-recorded to monitor the motor performance and for a more precise definition of movement onset (Ryun *et al*., 2014). Figure 1 shows the experimental protocol about acquisition of BP. The ECoG channels showing abnormal signals caused by pathology or technical problems were excluded from further analyses.

[Figure 1 insert here]

2.3. Signal preprocessing

The ECoG data were analyzed using Matlab software (Mathworks, Natick, MA). The recorded data were down-sampled to 200 Hz for unification of the various sampling rates

in the analysis. The movement onsets were determined based on the EMG signals. All trials were averaged with a time window of 5 seconds covering a period from 4 seconds before movement onset to 1 second after. Finally, channels that represent the features of BP were chosen among the electrodes in the PFC. Figure 3 demonstrates representative examples of "classical" two-component intracerebral BPs. The waveform in Subject 5 has typical BP characteristics; 1) The early BP shows an initial slowly increasing negativity with a hardly discernible onset. 2) The late BP becomes steeper than the early BP and appears approximately 500 ms before the task-relevant EMG activity. For the connectivity analysis, the time windows of 500 ms were separately selected in the early BP, late BP, and baseline period. Each time window was determined in the middle of each component. To compare the intraregional connectivities between the PFC and the non-PFC regions, non-PFC electrodes were selected outside the PFC and the motor related area. Figure 2 shows electrode location with brain model.

[Figure 2, 3 insert here]

2.4. Connectivity analysis

Partial directed coherence (PDC) was used for the connectivity analysis (Baccala & Sameshima, 2001). PDC is a connectivity estimator in the frequency domain that is based on a multivariate autoregressive (MVAR) model. It provides a linear measure of causality representing the strength and direction of the interaction between multiple variables. Under self-paced movement conditions, we used PDC to estimate the connectivity patterns between subdural electrodes. According to the MVAR model, a multivariate process can be described as a data vector, *S*, of *M* source signals in time, *t*:

$$S(t) = (S_1(t), S_2(t), \cdots, S_M(t))^T.$$

The MVAR model can then be constructed as:

$$S(t) = \sum_{n=1}^{p} P(n)S(t-n) + E(t)$$

where $E(t)$ denotes the error of the MVAR model, which is the vector of white noise at time *t*. $P(n)$ is an *M* x *M* matrix comprehending the model coefficients, and p is the model order.

The MVAR model was transformed into the frequency domain as follows:

$$P(f)S(f) = E(f)$$

where f denotes frequency and $P(f) = -\sum_{n=0}^{p} P(n)e^{-i2\pi f n\Delta t}$ with $P(0) = I$ (I is the identity matrix).

The PDC factor from *j* to *i* is given by

$$\mathrm{PDC}(f) = \frac{P_{ij}(f)}{\sqrt{p_j^{\mathrm{H}}(f)p_j(f)}}$$

where $P_{ij}(f)$ is the *i, j*-th element of $P(f)$.

PDC values are represented as a range from 0 to 1. Values close to 1 indicate that most of the signal in source i is caused by the signal from source j. Conversely, values close to 0 indicate that there is little information flow from source j to i at a particular frequency, *f*. Although the PDC can examine any range of frequencies, a frequency band of 1-50 Hz was used in our present study. Detailed information regarding the method is described in our previous study (Kim *et al*., 2010). We used a window size of 500 ms to estimate the PDC. PDCs of different time ranges (e.g., baseline, early BP, and late BP) were estimated by sliding the window. The PDC spectra were analyzed from 1 to 50Hz, which were further divided into sub-bands; delta (1~3 Hz), theta (4~7 Hz), alpha (8~12 Hz), beta (13~30 Hz),

and gamma (31~50 Hz). The statistical significance of the PDC value was determined by fisher's z-transformation at a significant level of 0.05. The differences between the baseline and BP stage were tested statistically using the Wilcoxon signed rank test. The Wilcoxon signed rank test is a non-parametric statistical hypothesis test used when comparing two related samples or matched samples to assess whether their populations mean ranks differ.

3. Results

3.1. The connectivity change according to the BP stage in the PFC

Results of connectivity of frequency bands show a difference between the baseline and BP phases in the ECoG records of 5 patients. Table 2 and Figure 4 show the percentage increase in connectivity in the PFC according to each frequency band. Compared to the baseline, most of the frequency bands show increasing connectivity during the BP. In particular, remarkable increases were present in the beta and gamma band.

[Figure 4 and Table 2 insert here]

3.2. An amount of gamma connectivity: comparison between PFC and non-PFC

Gamma band connectivity in the PFC of 5 patients revealed a marked increase compared with that in the non-PFC regions. In comparison with the baseline, during the build-up to a BP, on average, gamma connectivity increased by 24.4% in the PFC, while it decreased by 31.4% in the non-PFC regions. Subject 1 showed a 33.5% increase in the PFC and a 42.4% decrease in the non-PFC regions. Subject 2 showed a 26.3% increase in the PFC and a 42.2%

decrease in the non-PFC regions. Subject 3 showed a 22% increase in the PFC and a 24% decrease in the non-PFC regions. Subject 4 showed a 15.9% increase in the PFC and a 17.2% decrease in the non-PFC regions. Subject 5 showed a 20.8% increase in the PFC and a 4.9% decrease in the non-PFC region. Figure 5 shows the gamma connectivity increase and decrease compared with the baseline and the BP in the PFC and non-PFC regions.

[Figure 5 insert here]

3.3. Spatial patterns of gamma connectivity in the PFC and non-PFC regions.

We consider a PDC value of $P<0.05$ as significant by Fisher's z transformation. We compared the intraregional connectivity in the PFC and non-PFC regions. Figure 6A shows the difference in amount and strength of conectivities between the PFC and the non-PFC regions during the BP stage. All subjects show a much stronger connectivity in the PFC area than in the non-PFC areas.

[Figure 6 insert here]

The amount of connectivity of the intraregional BP increased according to the BP stage

(Figure 6B). In the case of the PFC, the mean PDC values are 0.238 in the baseline, 0.295 in the early stage of BP, and 0.319 in the late stage of BP. In the case of the non-PFC, the mean PDC values are 0.264 in the baseline, 0.257 in the early stage of BP, and 0.214 in the late stage of BP. Note that gamma connectivity in the PFC increased until immediately prior to movement onset ($p<0.05$, Wilcoxon signed ranks test), while gamma connectivity in the non-PFC decreased ($p<0.05$, Wilcoxon signed ranks test).

4. Discussion

4.1. Relationship between BP and connectivity

The intraregional connectivity is involved in building a BP. This study shows an increased beta and gamma connectivity among multiple ECoG channels in the human PFC immediately before the self-paced movement. The increased connectivity indicates synchronous activity between the neurons within the PFC for movement preparation. The information exchange at the neuronal level induces synchronous cortical activity. Thus, the intraregional connectivity would be accompanied by a BP. Our first analysis (Figure 4) of an increased PFC network connectivity during self-paced movement supports the idea that connectivity is associated with the generation of a BP. In addition, this increase in connectivity dominantly occurred in the gamma band (30-50 Hz), suggesting that the gamma band takes the lead in the interactions in the PFC.

The connectivity in the BP period is dynamic, the more the connectivity increases, the bigger the BP, as shown in Figure 6B. This simultaneous increase in the BP and intraregional connectivity occurs consistently in all 5 subjects, implying that the neuronal

activity is synchronized according to continuous and accumulating information flow. Wu *et al*., showed that a Parkinson's disease (PD) patient, who had a problem with movement execution, had less connectivity between motor-related areas including the PFC. (Wu *et al.*, 2011), indirectly demonstrating that the interaction of brain networks is disrupted in PD patients during the performance of self-paced movement. However, Wu's study did not present the relationship between BP and connectivity. Our report is the first to show the relationship between intraregional connectivity and BP.

4.2. The role of PFC for BP

It has been recognized that the prefrontal cortex (PFC) plays a role in the preparation of various directions during voluntary movement (Jueptner *et al.*, 1997; Passingham, 1996). Increased movement intention is associated with great activation of the pre-SMA region (Lau, Rogers, Haggard, & Passingham, 2004). Conversely, a lesion in the PFC area including parts of the DLPFC can lead to a decline or a complete absence of a BP preceding movement (Singh & Knight, 1990; Wiese *et al.*, 2004), which may be ascribed to

the loss of attention and motivation also associated with abnormality to these regions (Singh & Knight, 1990). In our present study, we found a BP only in the PFC region as shown in Figure 3. Moreover, intraregional connectivity was correlated with BP in the PFC, but not in the non-PFC regions. Conversely, the connectivity during a BP period was decreased in the non-PFC regions, implying that the PFC is a key region in the generation and build-up of the BP by means of reinforcement of information exchange.

4.3. The role of gamma activity in BP

The manner in which frequency multiplexing occurs between brain's regions involved in development of BP is not known. In the present results, we demonstrate a significant beta and gamma band connectivity in the PFC. The most prominent connectivity increase during a BP was found in the gamma band. Extensive studies support the fact that gamma oscillation is related to the motor and sensory processing required for cognitive execution of the task. Indeed, gamma oscillations have been described in a variety of sensory (Cardin *et al*., 2009), perceptual learning (Gruber, Muller, & Keil, 2002), and movement

execution (Cheyne, Bells, Ferrari, Gaetz, & Bostan, 2008). Recent studies have reported that gamma oscillation is elicited during voluntary movement in primary motor cortex (Cheyne *et al.*, 2008) and anterior supplementary motor area (Ball *et al.*, 2008). Gamma oscillation induced by voluntary movement indicates the activation of cortico-subcortical networks involved in the feedback control of movements (Cheyne *et al.*, 2008). In addition, an increase in cortico-muscular coherence in the gamma band was observed in the motor cortex during preparation of the response to a visual stimulus (Schoffelen, Oostenveld, & Fries, 2005). In short, gamma oscillation may reflect various temporal dynamics of cortical networks and their interactions. Gamma oscillation activity has been found over the frontal lobe during a top-down task. It may possibly reflect the activation of executive networks involved in decision making (Kaiser and Litzenberger, 2004). In respect to connectivity, slow oscillation such as alpha, delta, or theta is known to be observed in long-range connectivity, while fast oscillation such as gamma is involved in short-range connectivity. Mostly, gamma connectivity takes part in local recruitment and task-related functions (Buzsaki & Draguhn, 2004; von Stein & Sarnthein, 2000). When

considering the role of gamma oscillation, gamma connectivity, which is increased with the development of a BP may be reflected information flow for the preparation of movement.

4.4. Development of early and late BPs

BP is divided into early and late stages. The early BP is developed slowly from 1500 ms to 500 ms before movement onset. The late BP follows the early BP and has a relatively steep slope. The early BP reflects intention and decision processes, and the late BP is associated with movement control and preparation (Shibasaki & Hallett, 2006). According to the progression of early and late BPs, the strength of intraregional connectivity is also increased (i.e. the connectivity in the late BP is stronger than that in the early BP, Figure 4), implying that BP and connectivity are closely related. In the early BP, decisions regarding the intention and timing were made mainly in the PFC. Thus, decision information may accumulate and elevate the intraregional connectivity in the PFC. The late BP, which is thought to be more a specific preparation of movement such as aspects of precision,

discreteness and complexity, needs more information for complex movement execution and increases more drastically than the early stage. Consequently, our results suggest that fine movement may finally be prepared through information exchange.

4.5. Connectivity decreases in the non-PFC regions during BP.

In the connectivity results, we found that connectivity simultaneously increased with BP in the PFC area. In contrast, the connectivity decreased in the non-PFC regions (Figure 5). This result may be interpreted as an aspect of distribution of attention. The connectivity in the non-PFC regions that are uninvolved in BP generation was decreased by attention on movement preparation. Jiang *et al*., showed that the connectivity of the movement-related area such as the left M1, left PMC, and left SPL increased, but the connectivity of the left superior cerebellum, left dentate nucleus, right cuneus, and left basal ganglia decreased during the movement state comparing to the resting stage (Jiang, He, Zang, & Weng, 2004).

4.6. Limitations

There are two concerns which should be discussed in interpretation of our results. Firstly, in the PDC analysis, the meaning of the connectivity at a frequency band is not directly related to the activity at the specific frequency band. Connectivity using an MVAR model is more sensitive to the change of signal phase than amplitude. Our results from the PDC analysis do not mean gamma oscillation activity itself but connectivity in the gamma band. Nevertheless, we showed an increase of the intraregional connectivity in the PFC according to the BP stages. Further study may be needed in order to investigate the correlation between connectivity and BP.

The second issue is that the increase of connectivity may be affected by the volume conduction effect. Similar signals can be picked up at adjacent electrodes, causing an increase of connectivity. However, we compared the connectivity between different time windows and different regions at the same electrode distribution. For the temporal difference, we compared the connectivity among the baseline, the early BP and the late BP. For the spatial difference, the connectivity within the PFC area was compared with the connectivity within the non-PFC area. Thus, the change in connectivity in our study is

likely not caused by the volume conduction influence.

4.7. Conclusions

In conclusion, this is the first study that reveals an increased gamma connectivity among multiple ECoG channels in the human PFC during self-paced movement. The prefrontal cortex participates in the modulation of movement, an aspect of preparation building up gamma oscillation connectivity. Gamma oscillation plays a role in binding multiple inputs from a diverse area. Our results demonstrate that intraregional connectivity is involved in the build-up of a BP and suggest that the amount of information in the PFC is important for the preparation of movement.

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List of Figure

Figure 1. The experimental protocol.

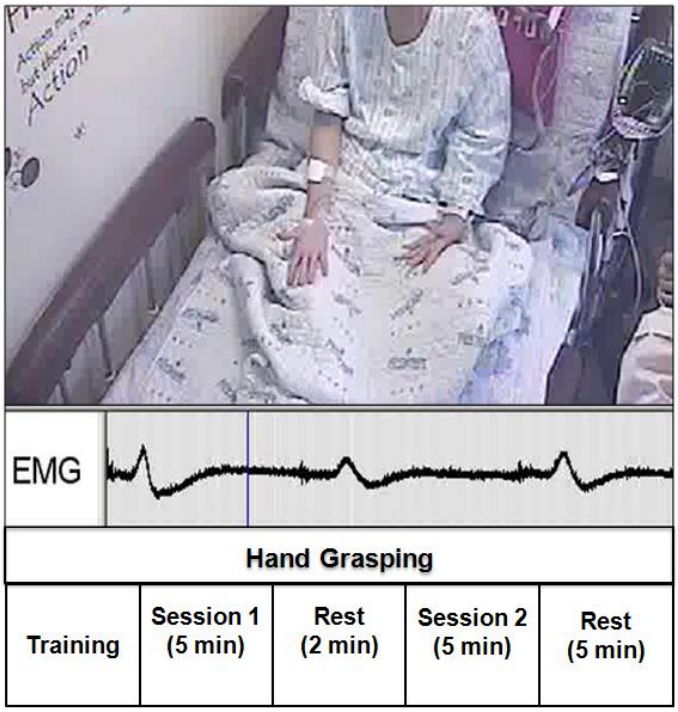


Figure 2. The electrode location of 5 subjects. Red dot indicates channel in PFC. Blue dot indicates channel in non-PFC area.

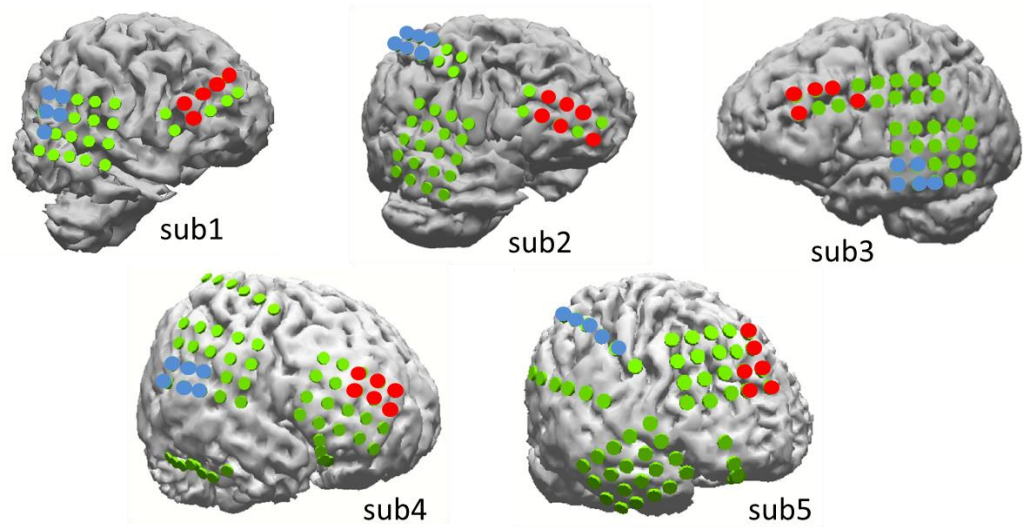


Figure 3. The Bereitshcaftspotential (BP) of 5 subjects. Each of the electrodes in the PFC represents a feature of BP; a classical two components before movement. Dashed line in blue indicates the starting point of BP1. Dashed line in red indicates the starting point of BP2. Subjects 2, 4 and 5 have distinct BP1 and BP2 stages, while subjects 1 and 3 have undistinguishable BP components.

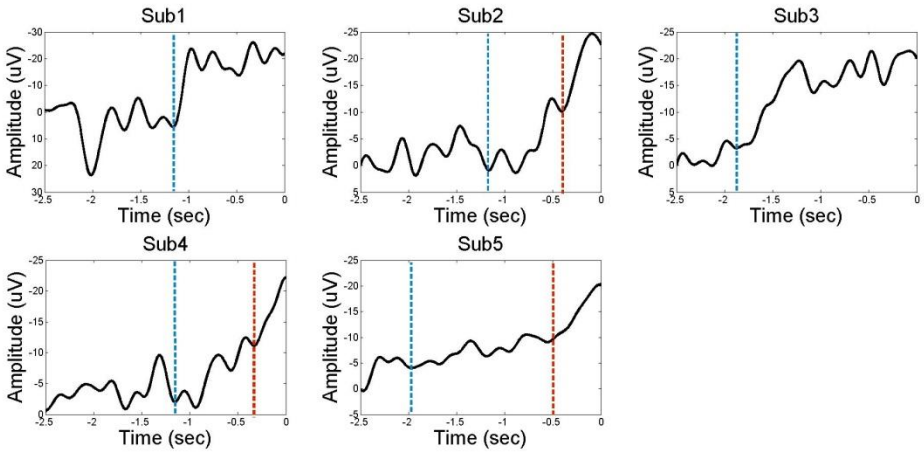


Figure 4. The connectivity change of frequency bands during a BP in the PFC

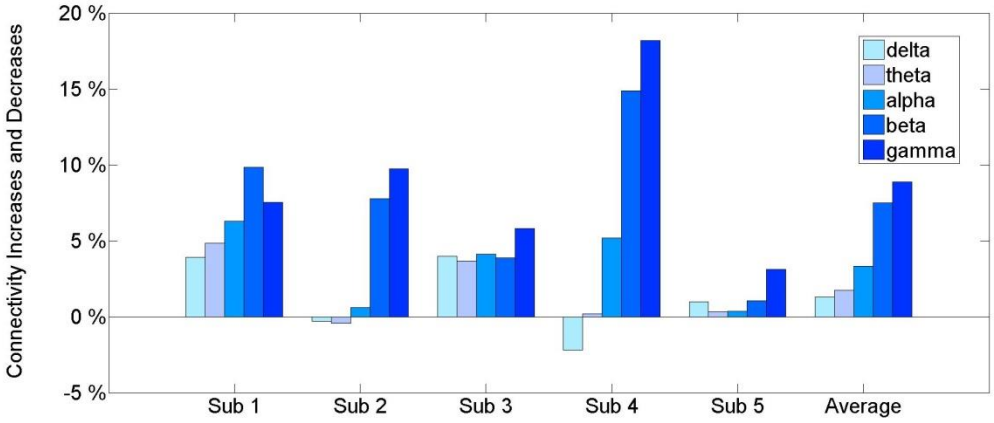


Figure 5. The amount of gamma connectivity increases and decreases in comparison with the baseline and BP between the PFC and the non-PFC regions.

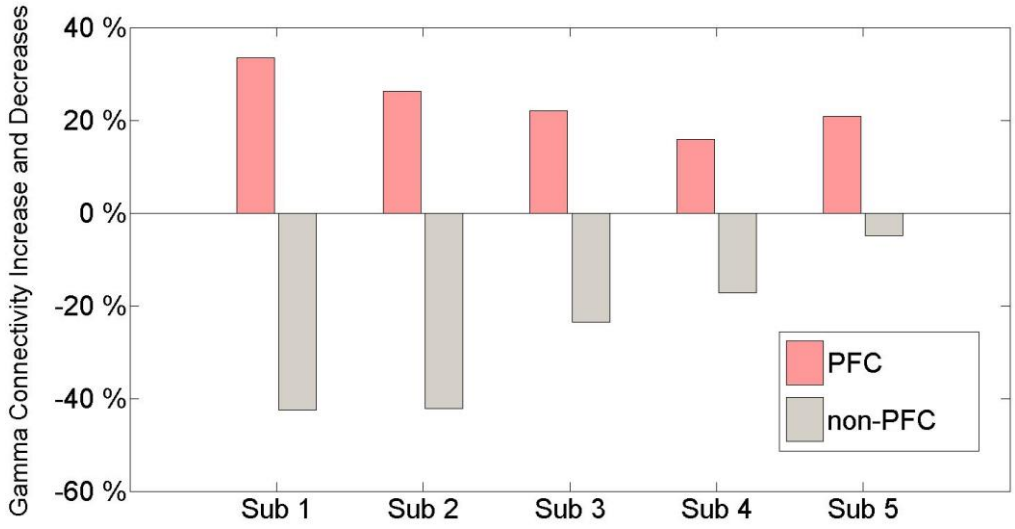
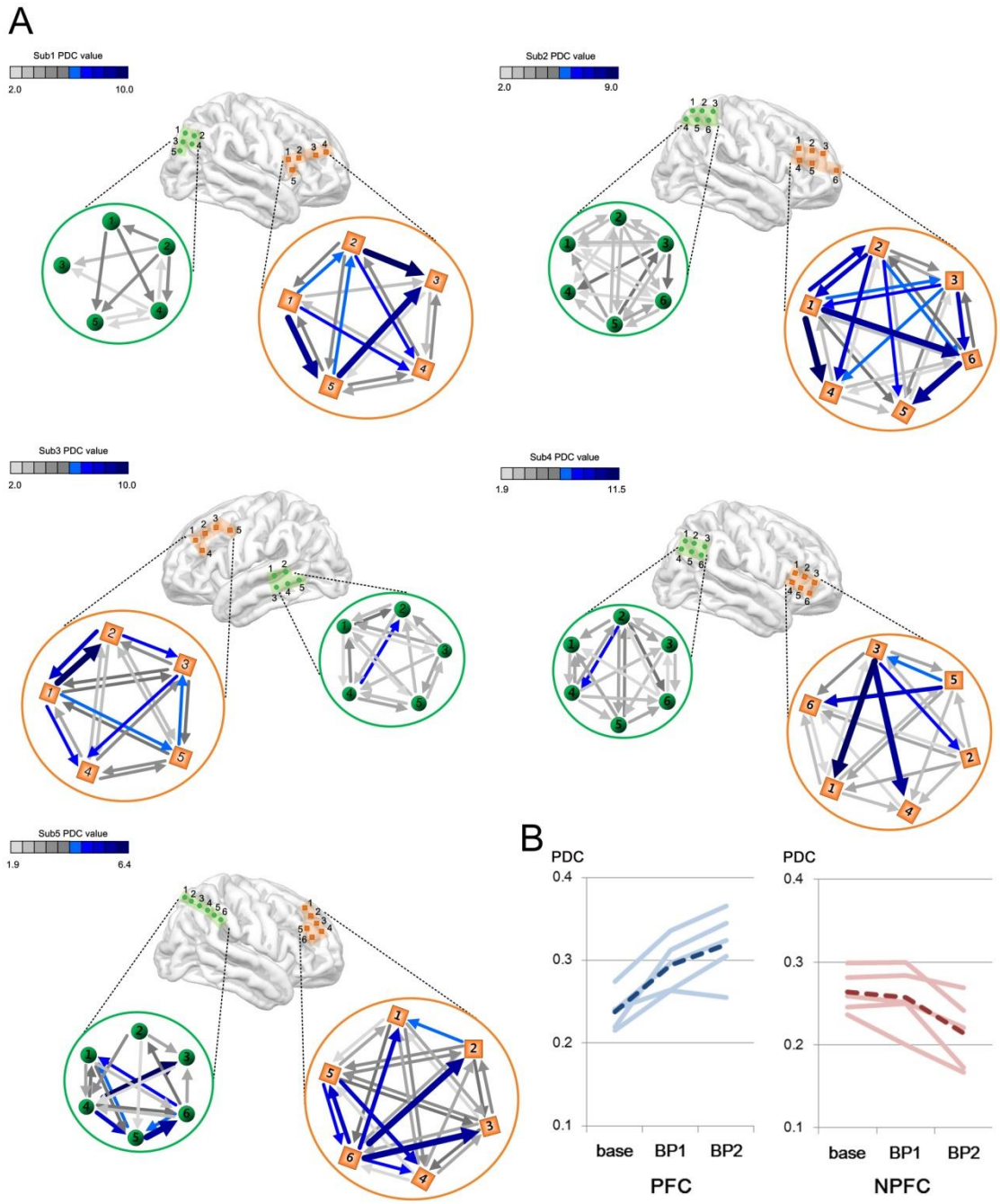


Figure 6. (A) Differences in gamma connectivity strength between the PFC and the non-PFC regions during the BP stages. Color bar shows the strength of connectivity from the PDC. Light green color indicates a weak PDC connectivity, whereas a dark blue color indicates a strong PDC connectivity. Each connectivity value is calculated by PDC measures and a PDC value of $P<0.05$ is considered as significant. (B) Change in gamma connectivity by the BP development stage. Blue lines indicate PDC value in the PFC. Red lines indicate PDC value in the non-PFC regions. Solid lines indicate individual subjects' connectivity change. Dashed lines indicate the mean of 5 subjects' PDC change.


A
Sub1 PDC value
2.0
10.0
Sub2 PDC value
2.0
9.0
Sub3 PDC value
2.0
10.0
Sub4 PDC value
1.9
11.5
Sub5 PDC value
1.9
6.4
B
PDC
0.4
0.3
0.2
0.1
base
BP1
BP2
PFC
PDC
0.4
0.3
0.2
0.1
base
BP1
BP2
NPFC

List of Table

Table 1. Clinical profiles.

Subject	Sex	Age	Side of hand movement	Location of intracranial electrodes	
				Location	Number
1	F	30	Left	Right F,P,O	88
2	M	36	Left	Right F, P	52
3	F	26	Right	Left F,T	48
4	M	37	Left	Right F,P,O,T	82
5	F	28	Left	Right F,P,T	58

Abbreviations: F, frontal; P, parietal; T, temporal; O, occipital;

Table 2. Connectivity change of frequency bands during a BP in the PFC

		Delta	Theta	Alpha	Beta	Gamma
Sub1	value	0.018	0.023	0.03	0.047	0.036
	(%)	7.8	9.71	12.56	19.72	15.06
Sub2	value	0.001	0.002	0.002	0.027	0.033
	(%)	-0.57	-0.85	1.24	15.55	19.51
Sub3	value	0.019	0.019	0.022	0.022	0.031
	(%)	7.96	7.36	8.27	7.77	11.62
Sub4	value	0.01	0.001	0.024	0.064	0.066
	(%)	-4.37	0.38	10.35	29.76	36.36
Sub5	value	0.006	0.008	0.016	0.032	0.036
	(%)	2.56	3.45	6.63	14.98	17.76

초록

배경: 운동준비전위(Bereitschaftspotential)는 움직임 전에 뇌파에서 나타나는 완만한 음성전위로 움직임에 대한 의도, 실행, 조절에 관여한다고 알려져 있다. 전전두엽(Prefrontal cortex)은 운동준비전위를 발생시키는 하나의 발생원으로 움직임에 관한 의사결정과 인지적인 준비에 있어 중요한 역할을 담당한다. 움직임 준비에는 다양한 신경세포들의 동기화된 활성화가 필요하기 때문에, 운동준비전위는 움직임과 관련된 신경세포들 사이의 정보 전달을 통하여 발전할 것이다. 그러나 정보전달의 방식과 운동준비전위 사이의 관계는 아직 명확히 밝혀져 있지 않다. 본 연구에서는, 전전두엽의 연결성이 운동유발전위가 발생하는 동안 어떻게 변화하는지를 알아보았다.

방법: 5명의 뇌전증 환자에게서 뇌파도(Electrocorticogram)를 기록하였다. 각 피험자는 5분동안 자기 주도하에 손을 쥐었다 펴는 과제를 세 번 반복하여 수행하였다. 전전두엽 영역에서 운동준비전위를 잘 나타내는 전극들이 선택되었고 전전두엽과 떨어진 영역에서 같은 수의 전극이 비교 모델로 선택되었다. 전전두엽 영역과 전전두엽이 아닌 영역 내의 연결성을 비교하기 위하여 Partial Directed Coherecne (PDC) 분석을 진행하였다. PDC의 값이 0에 수렴할수록 영역간 간섭성(coherence)이 작고, 1에 가까울수록 영역간 간섭성이 큰 것을 의미한다.

결과: 운동준비전위가 발달하는 동안 전전두엽 영역에서 베타(Beta)와 감마(gamma) 밴드 뇌파 연결성이 평균적으로 24.4% 증가하였다. 반대로 전전두엽이 아닌 영역에서는

감마 밴드의 뇌파 연결성이 평균적으로 31.4% 감소하였다. 전전두엽에서 영역내의 연결성증가는 운동준비전위의 발달 정도에 따라 함께 증가하였는데 기저선의 연결성 값은 0.24, 이른 운동전위의 연결성 값은 0.30, 늦은 운동준비전위의 연결성 값은 0.32로 나타났다.

중요성: 운동준비전위 동안 전전두엽에서 나타난 감마 밴드 뇌파 연결성의 증가는 전전두엽 신경세포간의 정보전달의 증가가 영역간 연결성에 의해 나타나는 것을 의미한다. 이러한 결과는 뇌 연결망 네트워크의 활성화가 움직임 준비에 관여한다는 것을 반영한다.

주요어: 운동유발전위, 뇌파도, 연결성, 전전두엽, 움직임 준비

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