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Power spectral density changes and language lateralization during covert object naming tasks measured with high-density EEG recordings

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ABSTRACT

Our objective was to study changes in EEG time-domain power spectral density (PSDt) and localization of language areas during covert object naming tasks in human subjects with epilepsy. EEG data for subjects with epilepsy were acquired during the covert object naming tasks using a net of 256 electrodes. The trials required each subject to provide the names of common objects presented every 4 seconds on slides. Each trial comprised the 1.0 second before and 3.0 seconds after initial object presentation. PSDt values at baseline and during tasks were calculated in the θ , α , β , low γ , and high γ bands. The spatial contour plots reveal that PSDt values during object naming were 10–20% higher than the baseline values for different bands. Language was lateralized to left frontal or temporal areas. In all cases, the Wada test disclosed language lateralization to the left hemisphere as well.

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1. Introduction

Cerebral lateralization of essential language activity is an important component of the evaluation of patients with medically refractory epilepsy who are candidates for surgical therapy. For more than a half-century the intracarotid sodium amytal procedure, known as Wada test, has been the standard by which this determination has been made [1]. Being an invasive procedure, the Wada test is associated with some risk and discomfort. Because of this, in recent years, a burgeoning interest has developed in replacing the Wada test with noninvasive measures. Some of these newer techniques, like the Wada test, are based on “deactivation” of the language cortex, such as repetitive transcranial magnetic stimulation [2], whereas other methods are based on structural imaging analyses [3]. However, the most promising novel noninvasive methods include direct measures of physiological language activation. Some newer methods include event-related brain potentials [4] and whole-head magnetoencephalography [5–7]. The other alternative activation techniques are based on hemodynamic responses to language activation, such as functional

transcranial Doppler [8], single-photon-emission computed tomography [9], positron emission tomography [10], near-infrared spectroscopic mapping [11], and functional magnetic resonance imaging [12]. All of these newer methods have variable limitations, and none have yet supplanted the Wada test as the “gold standard” for lateralizing cerebral language dominance.

Among the aforementioned approaches, the most simple and least costly are based on scalp EEG measurements. Multichannel EEG devices are readily available in most clinical sites and could thus be used to replace the invasive Wada test. Therefore, our aim was to establish an EEG-based language lateralization test. Here we present initial results for four patients with epilepsy examined in an object naming task with 256-channel EEG time-domain power spectral density (PSDt) computations. It was found that PSDt values during object naming tasks were 10–20% higher than the baseline values for different frequency bands. Lateralization to the left cerebral hemisphere in spatial plots of PSDt was also observed, and these results were similar to those from the Wada test for all four subjects. The notation PSDt is used to emphasize that it is the power spectral density of the time-domain EEG data and it is different from the spatial power spectral density (PSD_x or PSD_z) of scalp EEG data. Such notations are becoming very common in the EEG literature [13,14].

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2. Methods

EEG data were acquired during the task using a net of 256 electrodes (Electrical Geodesics, Inc., Eugene, OR, USA), which provides, roughly, an interelectrode separation of 2.0 cm. The whole net covers the head, back of the neck, and also the face and eye areas. The EEG was acquired with a sampling rate of 250 Hz, that is, 250 samples/second. Data were collected with reference to the central, Cz, electrode by using a high-pass filter of 0.1 Hz and a low-pass filter of 100 Hz. The data were then referenced to the common average reference while doing the data cleaning and analysis.

Data for four subjects were used for this study. All subjects had medically refractory localization-related epilepsy and all were candidates for epilepsy surgery. This study was conducted prior to surgery. Results of preoperative intracarotid sodium amytal testing disclosed that essential language function was lateralized to the left side in all cases. The data were collected at the Regional Epilepsy Center located at the Harborview Medical Center, University of Washington, Seattle. Data collection and the subsequent data analysis were governed by protocols approved by the institutional review board of the University of Washington.

The trials required each subject to provide the names of common objects presented on a computer screen. A few examples of the objects used were a pencil, a chair, a television, a lamp, and a cat. Subjects were asked to name the objects covertly, that is, silently. Each trial comprised the 1 second before and 3 seconds after initial object presentation. The 1-second data before the presentation constituted the baseline. There was also a random pause of 3–5 seconds between each trial. Each subject underwent 80 trials; this means that 80 objects were shown on the computer screen and the corresponding data collected. Actual recording time for data collection is about 15 minutes. When preparation time, instrument check, etc., are included, the total time for collection of data for each subject was 45 minutes. No subjects were excluded from the study. Data for one subject were noisy due to facial muscle artifacts, and we were able to extract only 15 good trials. Therefore, for other subjects we used only the first consecutive 15 good trials even though there were more than 15 good trials. The consecutive trials were selected to avoid any bias in the selection process.

2.1. Artifact removal

Data were first high-pass filtered with a 2.5-Hz filter to remove the low-frequency muscle artifacts and any linear drift in the data. Independent component analysis (ICA) technique was then used to remove eye movements, eye blinks, and other artifacts from the continuous EEG data [15]. The spatial patterns of the ICA components were plotted and identified as related to eye movement or facial muscle activity. These components were then removed. The cleaned continuous EEG data were segmented into trials. For each subject, the trials on which the EEG amplitude values were above ± 100 μ V were manually rejected. This was performed with EEGLAB software from the University of California at San Diego [16]. For each subject, the best 15 trials with no artifacts were selected for further analysis.

Time-frequency filtering of the data was performed with a matching pursuit filter [17,18] to eliminate the 60-Hz power line artifact. The method is based on the Matching Pursuit algorithm, but it uses atoms that are distributed in both time and space. This cleaned data set was then used for PSDt computations.

2.2. PSDt computations

The EEG data for each trial were analyzed in the θ (3–7 Hz), α (7–12 Hz), β (12–30 Hz), low γ (30–50 Hz), and high γ (50–100 Hz) bands. The data were filtered in each band with an equiripple

Parks–McClellan bandpass filter. The gain was unity (0.0 dB) in the pass band and –60 dB outside the pass band. The ripples in the passbands were limited to a maximum of 0.02 dB. PSDt values for the baseline and during object naming tasks were calculated after Fourier transform of the EEG data. The object naming task data were 3.0 seconds long. The PSDt for each second of data was computed separately. This was done to examine the temporal behavior of the PSDt during the 3-second-long period. The PSDt values were then averaged over 15 trials. The same procedures were used for all four subjects.

Color intensity plots of the PSDt values were constructed using a montage of the layout of 256 electrode positions. For plotting purposes, only electrodes above eye level were used. This consisted of 125 electrodes that were uniformly distributed over the top of the head, forehead, temporal areas, and occipital area. This plotting area was sufficient to examine language-related activities during object naming tasks. The horizontal and vertical axes for plots are in normalized length units. Color bars in the plots are in arbitrary magnitude units. All data analysis was performed using MATLAB 7.4 (The Mathworks, Natick, MA, USA) software.

3. Results

The results of preoperative intracarotid sodium amytal testing disclosed that essential language function was lateralized to the left side in all cases. In the following we describe the results of the PSDt computation for each band of one subject. Thereafter, the results for all subjects are summarized.

3.1. θ (3–7 Hz) band activity

Contour plots of PSDt averaged over 15 trials at baseline and during the object naming tasks for the θ band are shown in Fig. 1. In the top row are plots for baseline and each second of the object naming tasks. Hereafter, we use the word task in place of object naming tasks. The bottom row of plots illustrate the differences between baseline and the task. The magnitude scale for the top row is different from that for the bottom row. This was done to visualize the differences in these plots. If the same scale were to be used for all of these plots, the difference plots would be dark blue, making it difficult to see changes in the spatial patterns. In all of these plots, the subject's nose is toward the top and subject's left is toward the left side of the figure. At lower edges and on the left and right sides of plots, PSDt values are higher. This could be due to a combination of muscle artifacts and brain activity in the left and right temporal areas and in the occipital areas.

The differences between baseline and task are very visible in the lower row of plots. There are some very interesting features to note. In the first second of the difference plot (bottom row, left plot), the differences are very close to zero, as illustrated by the mostly yellow area. However, in the next second of activity (bottom row, middle plot) the left frontal area shows an increase in PSDt values. There is a further increase in the third second of activity (bottom row, right plot), which could be related to the increased activity of the essential language area of the brain during the task. The change is about 30% in the essential language area in the third second as compared with the baseline value. This was computed by taking the mean intensity over the activation area at baseline and during the task. The activation area was determined by visual inspection of the contour plots of the task. The same activation area was also used for computation of the baseline values. The mean intensity above baseline during the task in the third second (bottom row, right plot) is about 360. The mean baseline value (top row, left plot) in the activation area is about 1200. This gives an increase of 30% above the baseline value during the

Fig. 1. Spatial plots of PSDt for the θ (3–7 Hz) band. Top row: Baseline and object naming tasks. Bottom row: differences in activity between the object naming tasks and baseline. Higher PSDt values at the edges in the top row of plots could be due to muscle artifacts. The difference plots in the bottom row definitely indicate language-related brain activity in the left anterior quadrant of the plots. Note that the magnitude scales are different for the top and bottom rows of plots.

third second of the task. In the second second (bottom row, middle plot), the lower area of the plot also shows increased activity. This could be a muscle artifact and might also contain some activity from the visual cortex. This is absent in the first- and in the third-second difference plots.

3.2. α (7–12 Hz) band activity

α band activity is illustrated in Fig. 2. The baseline shows higher activity in the left and right occipital areas for the visual cortex. In the same areas, activity increases from first second to the next during the task. It is noteworthy that during the first second of the task, visual cortex activity has decreased as compared with baseline; however, it increases in the second and third seconds and is definitely higher than baseline in the third second of the task.

The difference between the task and baseline activity is illustrated in the lower row of plots. In the first second, activity has increased in the anterior left quadrant, probably related to the language cortex. This language activity decreases in the second second and is almost negligible in the third second. Visual cortex activity decreases in the first second but becomes very strong in the third second. There is some activity in the left temporal area in the second second that is absent in the first second and decreases slightly in the third second.

3.3. β (12–30 Hz) band activity

In this band the left frontal area, related to the language cortex, is most active at baseline and also during the task (Fig. 3, top row). This activity seems to be very focused and very strong at baseline and also during the task. The difference plots in the bottom row

Fig. 2. Spatial plots of PSDt for the α (7–12 Hz) band. Top row: Baseline and object naming tasks. Bottom row: Differences in activity between the object naming tasks and baseline. Activation of the visual cortex is very strong in the third second. Refer to the right plots in the top and bottom rows.

Fig. 3. Spatial plots of PSDt for the β (12–30 Hz) band. Top row: Baseline and object naming tasks. Bottom row: Differences in activity between the object naming tasks and baseline. There is some activity related to the visual cortex in the first second of the difference plot (bottom row, left plot), which becomes much stronger in the third second (bottom row, right plot). During the second second, the brain response is minimal (bottom row, middle plot).

provide more details of the changes during the task. In the first second, the lower right and left areas, possibly related to the visual cortex, show some activity, which decreases during the second second but becomes very strong during the third second. The activity is also widely distributed in the lower half of the plot. The left frontal area, possibly related to language activity, also shows increased activity in the third second.

3.4. Low γ (30–50 Hz) band activity

The low γ band activity is very focused on the left side at baseline and also during the task (Fig. 4, top row). It is difficult to observe any differences in these plots. However, in the difference

plots in the bottom row, the activity is distributed more broadly. There is some higher activity in the possible language and visual areas. The change is about 10% in the language area as compared with baseline in the third second. Percentage changes in other areas are much larger (10–30%) as compared with baseline in the third second.

3.5. High γ (50–100 Hz) band activity

High γ band activity is very focused at baseline and during the task (Fig. 5, top row). This is very similar to the low γ band activity but the intensity values are much lower as compared with Fig. 4. The difference plots (Fig. 5, bottom row) also show that the activity

Fig. 4. Spatial plots of PSDt for the low γ (30–50 Hz) band. Top row: Baseline and object naming tasks. Bottom row: Differences in activity between the object naming tasks and baseline. The top row of plots show that activity is very focused at baseline and during the object naming tasks. However, the difference plots indicate that the brain activity is distributed widely, with some stronger activity in the anterior left quadrant that could be attributed to the essential language area in the brain.

High Gamma Band Activity

Fig. 5. Spatial plots of PSDt for the high γ (50–80 Hz) band. (Top row: Baseline and object naming tasks. Bottom row: Differences in activity between the object naming tasks and baseline. The top row of plots show that activity is very focused at baseline and during the object naming tasks. The difference plots also show that brain activity is confined to the same area as in the top row of plots. Some spatial differences are noticeable in the bottom row. This suggests that activity in the essential language area in the brain has some temporal distribution during the 3.0-second period of the object naming tasks.

is very focused. This is very different as compared with the wide distribution of low γ band activity. The change is about 17% above baseline values in the language area as compared with baseline in the third second. Such changes are also visible in the first- and second-second difference plots.

3.6. Analysis of the data of other subjects

The patterns described above were also observed in the data for the other three subjects. The language area was lateralized to the anterior left quadrant in all four subjects. PSDt plots during the tasks in the first, second, and third seconds for all subjects were slightly different. However, they did show patterns similar to those in Figs. 1–5.

For a comparative analysis, we selected the area in the anterior left quadrant of the plots that could be related to the language activity in the brain. The mean value of the percentage change above the baseline in each band for that area was computed for each subject. Values were averaged over the values for the first, second, and third seconds. These values are listed in Table 1. These mean values suggest that there is a measurable change in each band above the baseline during the silent object naming task that could be related to the language activity in the brain. We also subjected the mean values for the anterior left quadrant at baseline and during the task to one-way ANOVA. The mean values during the task were significantly ($P < 0.05$) different from the baseline values for all bands.

Table 1
Mean percentage change above the baseline during silent object naming tasks in the left frontal quadrant, possibly related to the language activity in the brain

	θ band (%)	α band (%)	β band (%)	Low γ band (%)	High γ band (%)
Subject 1	22	3	12	7	18
Subject 2	18	5	14	10	16
Subject 3	14	7	20	12	10
Subject 4	20	5	17	15	12
Mean $\pm$ SD	18.5 $\pm$ 3.4	5 $\pm$ 1.6	15.75 $\pm$ 3.5	11 $\pm$ 3.3	14 $\pm$ 3.65

A comparative analysis of left lateralization was also carried out with one-way ANOVA. This was performed for the difference plots. The mean value of PSDt of the left half was compared with that for the right half and was found to be significantly ($P < 0.05$) different in all bands.

4. Discussions and conclusions

These plots reveal that PSDt values during the object naming tasks were approximately 5–20% higher than baseline values in the anterior left quadrant of the plots. The maximal changes are lateralized to focal areas of the left cerebral hemisphere. This could be related to the essential language activity of the brain.

There is an increase in PSDt values in the lower right and left edges of the plots in the θ band. In these areas, contamination from muscle artifacts is a possibility even though these were silent object naming tasks. However, pickup of some brain activation is also a possibility that is more recognizable in the difference plots (see Fig. 1). The increased PSDt values in the anterior left quadrant of difference plots are definitely related to essential language activity of the brain. The α band plots (Fig. 2, bottom row) show strong activity in the visual cortex but very little activity in the essential language area. β band activity shows some activation of the essential language area in the third second of object naming tasks and strong activation of the visual cortex. Low and high γ band activity is very focused at baseline and during the object naming tasks. The difference plots show that low γ band activity is widely distributed, but high γ band activity is very focused in the possible essential language area.

The difference plots in the θ band (Fig. 1) and in the low γ band (Fig. 4) show similarities in the widespread activity. γ band activity is modulated by the oscillations of θ band activity [19]. This spreading of PSDt values in large areas could be related to θ and low γ band coupling.

High γ band activity and its dynamic time-dependent behavior have also been examined with subdural electrocorticographic (ECoG) recordings [20–22]. In our results with scalp EEGs, we do see some very focused high γ band activity related to the language

tasks (see Fig. 5). It also shows some time-dependent changes during the covert object naming task (see Fig. 5, bottom row). During the first-second (0–1 s ERP-Base) difference plot, there is very focused activity in the left frontal area. There is the main bright spot at coordinates (0.35, 0.50) and a smaller medium-intensity spot at coordinates (0.43, 0.60). Both spots are probably related to covert object naming activity. The main bright spot diminishes in the middle period between 1 and 2 seconds and then increases and slightly spreads during the period 2–3 seconds. The other smaller spot diffuses in a wider area after the period 0–1 second. These findings are not exactly similar to what was seen earlier [22] on invasive ECoG recordings. However, we are seeing a chronodynamic pattern in scalp EEG recordings during the covert object naming tasks that is somewhat similar to what was observed in ECoG recordings [22].

Our results suggest lateralization of the language area to the left hemisphere along with possible localization to the left anterior quadrant of the plots. In comparison, the Wada test lateralizes only language dominance. However, the Wada test also assists with memory assessment, whereas the EEG does not. Thus, the results reported here do not replace the results obtained with the Wada test, but supplement them. In summary, these results suggest that it may be possible to noninvasively lateralize, and even eventually localize, cerebral regions essential for language tasks from scalp EEG data. This could be very helpful in presurgical planning. These findings are preliminary and need to be further studied in a large population base.

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