Suitability of FFT Spectra versus DPA Period Spectra for Identification of Arousal States

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Introduction

To detect changes in arousal which often occurred during long duration DC MEG studies in our study of migraine, we found the present clinical method inadequate. Small fluctuations of arousal can not be quantified using the 5 stage scores available for NREM arousal states [1]. In addition, this scale is not linearly related to changes in the spectral activity observed in the MEG data. Therefore, we developed a zero crossing period measurement technique [2] with a built-in frequency selection filter (dynamic period analysis, DPA). DPA produces a period based power spectrum quantifying the dominant waveform activity recorded in a segment of data. For all subjects, changes of arousal level resulted in characteristic changes in the corresponding DPA spectra. This motivated us to apply a principal component analysis [3] to extract a set of principal component spectra for quantifying the small changes of arousal which we needed to detect. A set of DPA spectra were used in this analysis. Two principal spectral components were extracted and used to construct a single arousal parameter. Unlike clinical arousal scores (awake, stage 1, etc.), this arousal parameter is continuous and allows us to detect even small changes of arousal and quantify the associated DPA spectral changes. Because FFT methods of spectral analysis are more familiar, we attempted to construct a similar set of arousal parameters based on FFT spectra generated from sequential epochs of MEG data for these subjects. Unfortunately, the principal component analysis of these FFT spectra did not extract component spectra which described a common set of arousal changes shared by all individuals. Rather than corresponding to arousal states, the two FFT principal components primarily formed a basis for differentiating between individual subjects.

Methods

MEG recordings of spontaneous cortical activity obtained from six subjects were used to develop the two principal component DPA arousal state spectra. The MEG data were acquired with a 7 channel Neuromagnetometer (BTi model 607) equipped with second order gradiometers. The center channel was positioned at P3 of the international 10-20 EEG measurement system and 45 minutes of data was acquired from each subject lying on his/her side. This site was accessible to our MEG system and data recordings contained less muscle and eye movement artifacts. For these subjects, the data was partitioned into 100 second epochs and a DPA spectrum was generated for each epoch. For the principal component analysis, it was necessary to limit the frequency band to frequencies greater than 0.5 Hz. Characteristic amplitude changes of the DPA power spectra for these frequencies are sufficient to distinguish all states of arousal. FFT spectra were generated for these same epochs of data. These FFT spectra were constructed from the same 100 seconds data epochs by averaging seven FFT spectra obtained from data within 40 second time windows which overlapped by 75%. This is a commonly employed technique for constructing an average FFT spectrum for semi-stationary data when the FFT software incorporates a window function. Window functions are used to minimize significant leakage of spectral power from the true frequency component into other nearby frequency components [4, 5]. However, if the spectral properties of the data are not completely stationary throughout the data segment then window functions may weight the data in a manner in which the final FFT does not represent the average spectrum of the data. We used FFT software which incorporated a Hanning window to weight the data within each 40 second window prior to the FFT transformation [6]. The FFT frequency spectra were transformed to FFT period duration spectra such that they could be compared to the corresponding DPA spectra and also to consolidate the power of the high frequency components into fewer components such that shifts in power to lower frequencies occurring with drowsiness and sleep are given more weight in the mathematical analysis.

For two additional subjects, included in this study, simultaneous EEG recordings were made with electrode placements, P3-A2 and Cz-F2. The 45 minutes of EEG and MEG data were partitioned into 25 second epochs. DPA spectra were produced for the center channel of the sensor array and the epochs of EEG data were scored for

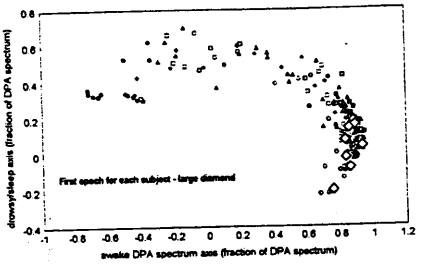

Fig. 1 Plot of β_{awake} and β_{drowsy} amplitudes for DPA spectra of eight subjects. Awake state nearly the same.

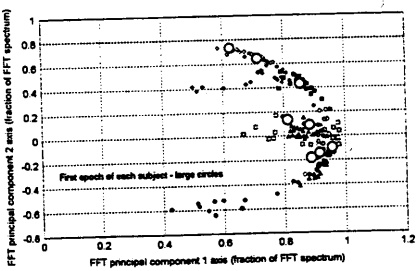

Fig. 2 FFT spectra principal component amplitudes for eight subjects. Awake state co-ordinates very different.

arousal state (awake, stages 1 - 4).

A principal component analysis was performed on the set of 162 DPA spectra from six individuals. Similarly, a principal component analysis was applied to the set of FFT spectra and two principal component spectra were generated.

Results

For the DPA spectra, the principal component analysis generated two principal component spectra. One spectrum was identical to the average awake spectrum of these subjects. The other component was found to be the time averaged power spectrum of waveforms which are present in the MEG data only in states of arousal other than awake. For any subject, a linear combination of the two principal component DPA spectra can be used to obtain a DPA spectra corresponding to the arousal state of the subject. Mathematically this relationship is:

$$DPA_{\text{arousal state}} = \beta_{awake}\, DPA_{awake} + \beta_{drowsy}\, DPA_{drowsy} + \text{Random}$$

with:
$DPA_{\text{arousal state}}$ = DPA spectrum of subject during an epoch of the study
DPA_{awake} = principal component DPA spectrum corresponding to awake state
DPA_{drowsy} = principal component DPA spectrum of waveforms occurring if not awake
β_{awake} = amplitude of the fraction of $DPA_{\text{arousal state}}$ which is associated with DPA_{awake}
β_{drowsy} = amplitude of the fraction of $DPA_{\text{arousal state}}$ which is associated with DPA_{drowsy}
Random is the spectrum of random spectral fluctuations that remain in the DPA spectrum

Using β_{awake} as an X coordinate amplitude and β_{drowsy} as a Y coordinate amplitude, the set of 162 DPA spectra for these six subjects are plotted in Fig. 1. In Fig. 1, the awake DPA spectrum generated from the first 100 seconds of data for each subject is closely aligned with the horizontal positive awake axis. Sleep state DPA spectra from subjects that were found asleep at the end of the study were at the other end of the arc of data points which defines an arousal state path through this two component vector space.

The results of the principal component analysis on the FFT spectra can be described by an equation similar to the DPA relationship above, except the awake state spectra for each of the six subjects were located very far apart in the X,Y coordinate system plot in Fig. 2. The awake spectra from the first epoch can not be used to define a set of awake state coordinates. While arousal changes are easily seen for each subject, there is no common state of arousal path. These FFT principal component spectra are seen to primarily differentiate the spectra according to properties unique to the individual rather than change of arousal state.

During the first 100 second epoch of the study each subject was awake. Therefore, in order to quantify individual spectral differences, we cross-correlated each DPA spectrum from this first epoch with the first epoch

DPA spectra of the other subjects. We did the same cross-correlation analysis for the FFT spectra. For the first 100 second DPA spectra the average cross-correlation for all subjects was 0.81. The corresponding FFT cross-correlation average was only 0.74. To quantify changes of spectrum due to a shift in the state of arousal we cross correlated the DPA from the first 100 second epoch to the DPA spectra generated from the 26 subsequent 100 second epochs of data for each subject. The same cross-correlations were performed on the FFT spectra. The average arousal state change cross-correlation for the DPA spectra was 0.70 and 0.91 for the FFT spectra. Thus, FFT spectra exhibit relatively large subject to subject differences and relatively small spectral change with shifts of the state of arousal. The DPA spectra have the opposite characteristics. Changes in the DPA spectrum caused by a shift in the arousal state are greater than the differences in spectra between individuals. This was investigated in more detail using the two subjects for which simultaneously recorded EEG data was scored for arousal state. In Fig. 3, the sequence of cross-correlation amplitudes of the first DPA to the subsequent 26 DPA spectra is plotted with the corresponding FFT cross correlations and the time series of arousal scores. In Fig. 3, the DPA spectra are characterized by large spectral changes with a shift in arousal state and the corresponding FFT spectra change much less. These differences in sensitivity to arousal state are easily seen in plots of individual DPA and FFT spectra. In Fig. 4, the awake state DPA and FFT spectra for this subject are over-plotted. In Fig. 5, the stage 2 arousal state DPA spectrum and the corresponding FFT spectra are plotted. Comparing Fig. 4 and Fig. 5, the DPA spectra exhibits greater shifts of spectral power between arousal states than the corresponding FFT spectra.

In Fig. 1, the state of arousal is observed to be defined by the angular location away from the horizontal awake spectrum axis and the maximum angle is approximately 140 degrees. Therefore, we defined a new arousal parameter to be equal to the angle of DPA spectrum plotted in these coordinates divided by 140. With this scaling, zero corresponds to the awake state and 1.0 would correspond to the stage 4 arousal state. However, stage 1, 2 and 3 are not located at equal intervals along this scale. The relationship of our arousal state score (0.0 to 1.0) to the present clinical scores is not linear.

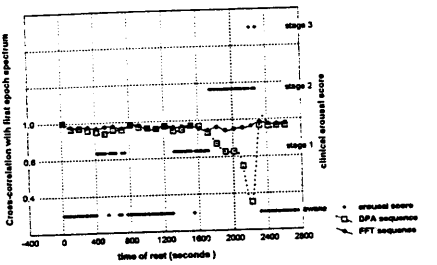

Fig. 3 The time series of DPA and FFT spectral change correlation amplitudes with the corresponding arousal scores.

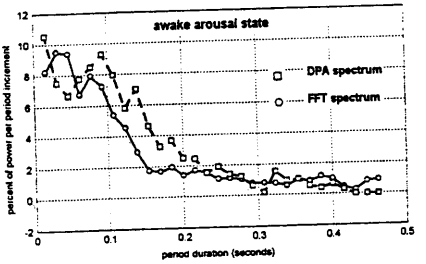

Fig. 4 The corresponding awake DPA and FFT period spectra.

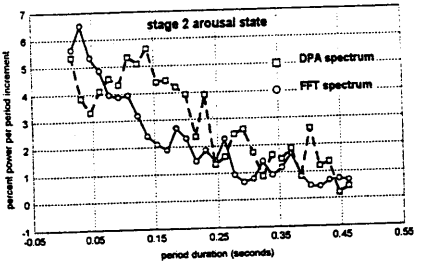

Fig. 5 The stage 2 DPA and FFT spectra.

For our data, mathematically,

log(DPA arousal score) = 1.15 (clinical arousal score) - 3.6

We used this relationship to predict the clinical arousal score from our DPA arousal score. In Fig. 6, the time series of predicted and actual scores are plotted. Both measures of arousal state display the same trends but do not completely agree at each epoch. While this plot is useful to those more familiar with the clinical scale, we find time

series plots of the β_{awake} and β_{drowsy} amplitudes of the DPA spectra to be more useful for assessment of changes of arousal state.

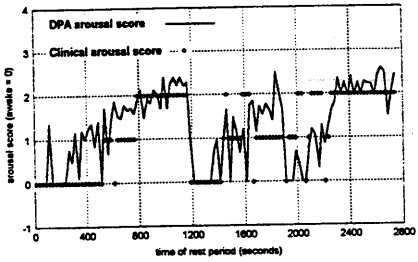

Fig. 6 Predicted arousal state score based on DPA parameters versus standard clinical scores.

Discussion

Assessment of the frequency content of data is primarily performed by either visual inspection or advanced mathematical techniques, such as FFT based power spectra. In this study, we demonstrated that the continuum of arousal state changes of MEG data can be quantified by applying a principal component analysis to DPA spectra and generating a set of unique arousal spectra. All DPA spectral changes occur in the corresponding FFT spectra. However, within the complete FFT spectrum the arousal related changes are small relative to subject to subject spectral differences. Thus FFT spectra are not suitable as a basis for development of arousal state parameters using a principal component analysis.

We use the arousal parameters, β_{awake} and β_{drowsy}, to identify and quantify amplitude and spectral changes of MEG data associated with shifts of the arousal state. However, these parameters may also be useful in assessing the physiological state of arousal based on changes observed in MEG or EEG data. The variability of the β_{drowsy} component may be especially useful for determining sleep onset.

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