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Functional brain imaging based on ERD/ERS

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Abstract

Sensory, cognitive and motor processing can result in changes of the ongoing EEG in form of an event-related desynchronization (ERD) or event-related synchronization (ERS). Both phenomena are time-locked but not phase-locked to the event and they are highly frequency-band specific. The ERD is interpreted as a correlate of an activated cortical area with increased excitability and the ERS in the alpha and lower beta bands can be interpreted, at least under certain circumstances, as a correlate of a deactivated cortical area. Spatial mapping of ERD/ERS can be used to study the dynamics of cortical activation patterns. Examples from a movement task are reported. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Event-related desynchronization (ERD); Event-related synchronization (ERS); Sensorimotor function; Voluntary movement; Brain oscillations

1. Introduction

Sensory and cognitive processing and motor behavior result not only in an event-related potential (ERP), but also in a change in the ongoing EEG in form of an event-related desynchronization (ERD) or an event-related synchronization (ERS). The former represents a short-lasting and localized amplitude decrease of rhythmic activity, the latter an amplitude increase. These reactivities are highly frequency-band specific and non-phase locked to the event. The ERPs are, in contrast, phase-locked reactions of the bioelectrical brain activity and explained by summation of synaptic potentials. Classical examples of ERD are, e.g. the blocking of occipital alpha rhythm after visual stimulation or the blocking of the central mu rhythm with active or passive movement (Pfurtscheller, 1992). Examples of ERS are, e.g. the enhancement of mu rhythms during visual stimulation (Koshino & Niedermeyer, 1975), the beta rebound after limb movement (Pfurtscheller, Pichler-Zalaudek, & Neuper, 1999) or the gamma activity induced during visual processing (Singer, 1993). The aim of this study is to give an example that the quantification of the ERD/ERS pattern in time and space in a simple finger movement task can give new insights in the dynamics of cortical networks.

2. Importance of the frequency of oscillations

The frequency of brain oscillations depends on the number of synchronously activated neurons. With an increasing number, the frequency becomes in general slower (Singer, 1993). Oscillations with 10 Hz comprise more synchronized neurons than oscillations with, e.g. 40 Hz. A simulation study performed by Lopes da Silva (1998) demonstrates the relationship between synchronously activated/inhibited neurons and frequency of brain oscillations. With an increasing number of interconnecting neurons and therewith an increasing number of coherently activated neurons, the frequency decreases and the amplitude increases. The lower alpha component has a larger spectral peak magnitude than the higher alpha component. For further details see Lopes da Silva and Pfurtscheller (1999) and Pfurtscheller and Lopes da Silva (1999a). It is also of interest to note that even if only a small fraction of the total population of neurons is synchronized, the resulting output may well overweigh the rest of the not-syn-

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chronized neural populations. Elul (1972) estimated that if only 10% of a population of neurons are synchronized, the amplitude is 10-fold the activity of the 90% of not-synchronized neurons. It was shown recently that, e.g. a self-paced brisk lifting of the index finger can activate neuronal networks in hand and foot representation areas resulting in bursts of beta oscillations with slightly different frequency in both areas (Pfurtscheller, Neuper, Pichler-Zalaudek, Edlinger, & Lopes da Silva, 2000). The frequency of these oscillations may be characteristic for the underlying neural circuitry.

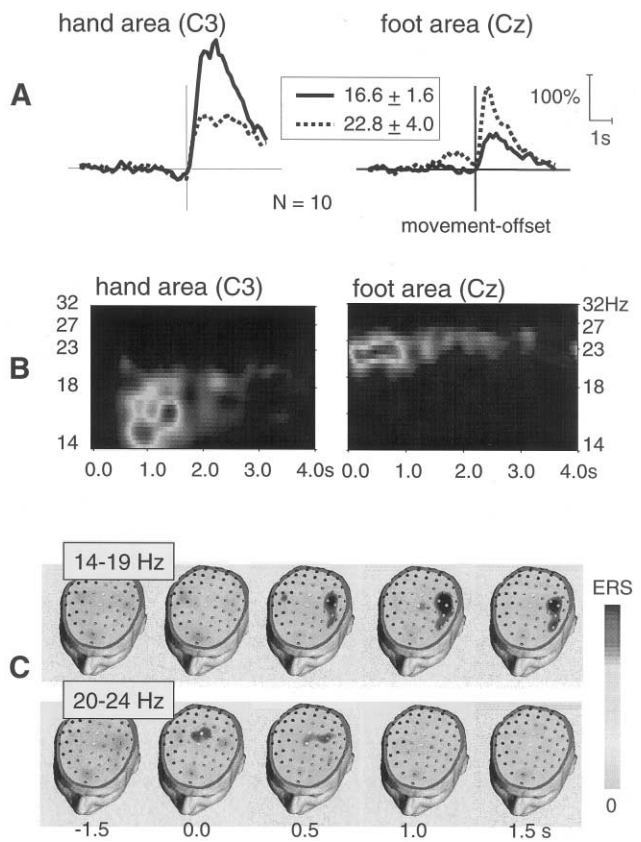

Fig. 1. Data from an experiment with voluntary right hand movement. (A) Grand average ERD/ERS time courses (ten subjects) calculated for electrode positions overlaying hand (C3) and foot areas (Cz) for the most reactive frequency bands. Data are triggered with movement-offset. Note the largest post-movement beta ERS around 17 Hz (full line) close to the hand area and around 23 Hz (stippled line) close to the foot area. (B) Example of a scalogram (wavelet analysis) obtained from one subject showing the most reactive frequency for data recorded over hand and foot areas. The peak frequency is 16.6 Hz for electrode C3 and 22.8 Hz for electrode Cz. (C) Series of maps from one subject calculated for the 14–19 and 20–24 Hz bands displaying the spatiotemporal patterns of the hand area beta ERS starting about 0.5 s after movement-offset and of the foot area beta ERS with a shorter latency.

3. Spatial mapping of ERD/ERS

One of the basic features of ERD/ERS measurements is that the EEG power within a predefined frequency band is displayed relative (as percentage) to the power of the same EEG derivations recorded during the reference or baseline period a few seconds before the event occurs.

The classical method to compute the time course of ERD includes the following steps:

1. bandpass filtering of all event-related trials;
2. squaring of the amplitude samples in each trial to obtain power samples;
3. averaging of power samples across all trials;
4. averaging over time samples to smooth the data and reduce the variability.

A modification applied to the discrimination between phase-locked and not phase-locked activity uses instead (ii) and (iii) the calculation of the point-to-point intertrial variance (Pfurtscheller & Lopes da Silva, 1999b). To obtain percentage values for ERD/ERS, the power within the frequency band of interest in the activity period is given by A, whereas that of the preceding baseline or reference period is given by R. ERD or ERS is defined as the percentage of power decrease or increase, respectively, according to the expression $\mathrm{ERD}\% = (A - R)/R * 100$[1]. For the display of the time course of ERD/ERS, a scale displaying either power changes with 0% in the reference period or relative power with 100% in the reference period is recommended (examples see Fig. 1A). Further details can be found elsewhere (Pfurtscheller & Lopes da Silva, 1999a).

For the determination of subject-specific frequency bands, the comparison of two short-time power spectra calculated by averaging over a number of event-related EEG trials can be used. One spectrum is calculated for the reference period (R) chosen some seconds before an event occurs, and the other is calculated for the activity period (A). In a movement task, this activity period can be selected, e.g. before movement-onset, during movement execution or after movement-offset. The difference curve between the two logarithmic power spectra of periods A and R, together with the 95% confidence interval, can be used to determine the significant frequency components, which either display a power increase (ERS) or power decrease (ERD) in the activity period as compared to the reference period (Pfurtscheller & Lopes da Silva, 1999a). Another method for subject-specific frequency detection is the wavelet analysis resulting in a scalogramm (Fig. 1B).

[1] In earlier publications (e.g. Pfurtscheller, 1992), the following definition was used: $\mathrm{ERD}\% = (R - A)/R * 100$. With this definition, negative numbers are obtained for ERS%. Because ERD is defined as power decrease and ERS as power increase it is more precise when the following expression is used: $\mathrm{ERD}\% = (A - R)/R * 100$.

Multichannel EEG signals are usually recorded against a common reference electrode. The data are therefore reference-dependent. To convert the reference-dependent raw data in reference-independent data, different methods are available which are discussed in detail by Lopes da Silva (1990). References to different deblurring methods, either using a realistic head model or a spherical model, can be found in van Burik, Edlinger, and Pfurtscheller (1999).

An example of a series of ERS/ERD maps calculated with spline surface Laplacian during self-paced right finger movement is displayed in Fig. 1C. For the calculation, a realistic head model was used (van Burik et al., 1999). The maps for the 14–19 Hz band display a beta ERS starting about 500 ms after termination of right hand movement and focused to the left sensorimotor hand area. In contrast, the 20–24 Hz band reveals a beta ERS focused to the mid-central area with a maximum in the first 500 ms after movement-offset. The data in the Figs. 1A and C can be interpreted that finger movement not only affects neural networks in the hand area but also has an impact on neural circuits in the foot area, whereby both networks show slightly different resonance-like frequencies (Pfurtscheller et al., 2000).

4. Interpretation of ERD/ERS

There is general agreement that a desynchronized EEG represents an activated level of cortical neurons (Steriade, Gloor, Llinas, Lopes da Silva, & Mesulam, 1991), therewith also the ERD can be interpreted as an electrophysiological correlate of an increased cortical excitability or an activated cortical area. In this relationship, a desynchronized occipital alpha rhythm is characteristic for processing of visual information and a desynchronized Rolandic mu rhythm is found during motor behavior and sensorimotor activation. So, e.g. a short lasting beta ERD with a magnitude of about 30% can be recognized in Fig. 1A in the ERD/ERS time course obtained from an electrode overlaying the hand area.

A desynchronized EEG means that in the underlying neural network or neuronal circuitry, small patches of neurons or neuronal assemblies work in a relative independent or desynchronized manner. In terms of information theory, a desynchronized system represents a state of maximal readiness and a maximum of information capacity (Thatcher, McAlaster, Lester, Horst, & Cantor, 1983).

Large amplitudes of synchronized alpha band activity can characterize brain states with reduced information processing and with no or little motor behavior. It is important to note that either the entire brain or only one specific neural system can be in an 'idling' mode. The term 'idling' was introduced by Adrian and Matthews (1934) to describe large amplitude oscillations over cortical areas which-at this moment of time — 'have nothing to do'. In this respect, a short-lasting enhancement of alpha band activity (alpha ERS) can be seen as a correlate of a deactivated cortical network.

Unilateral voluntary upper limb movement is accompanied by an ERD in the alpha and beta bands localized over the contralateral sensorimotor area (Pfurtscheller et al., 1999). This ERD can be followed by a beta rebound or beta ERS with a maximum within 1 s after movement-offset (see, e.g. Fig. 1C). In a recent study with transcranial magnetic stimulation (TMS) during internally paced voluntary finger movement, Chen, Yassen, Cohen, and Hallett (1998) reported on a significantly reduced excitability of corticospinal neurons in the first second after termination of movement. This time period corresponds to the occurrence of the post-movement beta ERS. This implies that the beta ERS with frequencies around 20 Hz can be interpreted, at least under certain circumstances, as a correlate of a deactivated cortical network (Pfurtscheller & Lopes da Silva, 1999b).

Summarizing, it can be hypothesized that there are three different states of cortical processing:

1. resting or neutral state without any specific processing of sensory, motor or cognitive information;
2. activated state with enhanced processing of information in a specific system, increased excitability of cortical neurons and characterized by an ERD;
3. deactivated state with reduced information processing in a specific system, decreased excitability of cortical neurons and characterized by an ERS in the alpha and/or lower beta bands.

Spatial mapping of ERD/ERS with a time resolution of, e.g. 125 ms can be used, therefore, to study the dynamics of cortical activation.

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