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Assessment of EEG Frequency Dynamics Using Complex Demodulation

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Summary

The complex demodulation (CD) approach was applied to human EEG recorded during a cognitive task performance, including voluntary goal-directed movements. The standard CD algorithm was extended by a simple procedure using frequency histograms and power spectra to select the characteristic frequencies of EEG segments around the task performance. In the majority of records, amplitude modulation was found, which decreased or disappeared in the period prior to and at the very beginning of the task performance. It was found that the decrease of modulation in fast beta and gamma components begins approximately one second before that of the alpha components. Frequency modulation appeared in some records at the end of the task in beta and gamma components. The results showed that a cognitive task performance is accompanied by non-linear processes in the frequency components of EEG. These dynamic changes could extend the findings of event-related desynchronization obtained by linear methods.

Key words

Complex demodulation • EEG • Hilbert transformation • Voluntary goal-directed movements

Introduction

The properties of complex demodulation (CD) to detect possible non-linear relationships of frequency components in the time course of a complex signal make this method attractive for studying biosignals of different origin. Despite some drawbacks related to the requirement for *a priori* information about the carrier frequency, CD has been successfully used for analysis of brain evoked potentials (EP) and electrocardiac signals (ECG). In the case of analyzing EP, CD has been used for detection of the response time and for extraction of the envelope and frequency of the transient wavelet (Childers and Pao 1972). In ECG, the method has been applied for assessing cardiovascular variables, overcoming the limitation of discrete Fourier transform (DFT) assuming stationarity of the signal (e.g. Hayano *et al.* 1993). The time-dependent changes in amplitude and frequency of the lower frequency (LF) and high frequency (HF) components have been traced in assessing the dynamic or phasic changes in the autonomic cardiovascular regulation (Hayano *et al.* 1994).

The strategy of the CD method is based on the discrete Hilbert transform which presents the signal in a complex (analytical) form. By calculating the instantaneous frequency and momentary power (envelope curve), the time-dependent changes of a particular frequency component can be traced when a single-component signal was analyzed. In addition to

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this approach, the CD method could be regarded as a band-pass filter which eliminates all other frequencies in the spectrum except for the selected one and hence can be applied to multicomponent signals.

The aim of this article was to present briefly the method of CD and mainly its application to EEG signals preceding voluntary finger movements. We wished to show the ability of this method to determine modulated segments of the signal, which reflect changes in the envelope and instantaneous frequency curves. In order to demonstrate the properties of this approach, it was tested on simulated signals containing the amplitude or frequency modulation of a selected frequency component. The time-dependent changes of EEG frequency components selected from the alpha, beta and gamma range were investigated for identifying the transients in EEG before, during and after performing a movement.

Methods

Signal analysis

The aim of CD is to obtain approximations of the amplitude and phase of a center frequency component f_0 from the time series as a function of time (Bloomfield 1976, Hayano *et al.* 1994). The estimation is based on the assumption that f_0 is known *a priori*, the so-called frequency of interest. The main idea of CD is to obtain a shifted and filtered version of the signal around f_0. This is attained by using an analytical form of the signal by the Hilbert transform and some transformation for shifting and filtering explained below.

By using the discrete Hilbert transform, the analytical signal of the time-series is calculated, the real part of which is the original signal $\{X_r(n)\}$ and the imaginary part $\{X_i(n)\}$ is the same signal but phase shifted by 90^0, i.e. the actual Hilbert transform. Supposing that the time-series X_t contains a component x_t which is characterized by slow changes of its amplitude and frequency around a center frequency f_0, this time-series could be expressed as:

$$X_t = x_t + z_t = A_t \cos(f_0 t + P_t) + z_t$$

where A_t and P_t are the slow changes of amplitude and phase of the frequency of interest, f_0 and z_t represent all frequency components existing outside the range of the slow fluctuations of f_0. Its analytical analogue is:

$$X_t = (1/2)\, A_t \{\exp[i(f_0 t + P_t)] + \exp[-i(f_0 t + P_t)]\} + z_t$$

The first step of the algorithm is to shift the frequency of interest to zero frequency in the spectrum. The shifting is performed by multiplying X_t and the complex sine term at a frequency f_0, i.e.

$$Y_t = X_t \exp(-i f_0 t) = (1/2) A_t \exp(iP_t) + (1/2) A_t \exp[-i(2f_0 + P_t)] + z_t \exp(-if_0 t)$$

The product Y_t contains the shifted component of the frequency difference at 0 Hz (first term), a component at a sum frequency $2f_0$ (second term) and all other frequency components (third term).

In order to preserve only the first term, Y_t should be low pass filtered without phase distortion:

$$y_t = (1/2) A_t \exp(i P_t)$$

After that the real and imaginary parts of the filtered signal are presented in a polar form and the amplitude A_t and phase P_t are obtained as curves vs time by:

$$A_t = 2|y_t|$$

$$P_t = \tan^{-1}\left[imag(h)/real(h)\right]$$

where $h = y_t/|y_t|$

As the slope of the P_t curve indicates deviations of the frequency F_t around f_0, the instantaneous frequency F_t vs time is obtained as a first derivative of the phase curve

$$F_t = f_0 + dP_t/dt$$

In this study the filter used was an infinite impulse response (IIR) of the Butherworth type. This filter leads to phase shifts, which we avoid by using the function "filtfilt" from the MATLAB package. Thus the non-linear phase distortions are eliminated.

When the method is used for e.g. ECG signals, the frequency components of interest are only two, i.e. the LF and the HF. These can be distinguished enough to be separated. The EEG signals, however, contain many spectral components placed close to each other. It is necessary to choose the frequency components in those ranges that are supposed to be significant for the investigated process. In the present study, the dynamics of alpha, beta and gamma frequency bands was of primary interest. We regard these frequency bands with respect to the activation and deactivation of brain rhythmicity, the so-called event-related synchronization (ERS) and desynchronization (ERD) prior to and during voluntary movement performance. (Pfurtscheller and Aranibar 1979).

In order to select f_0 for the significant narrow frequency bands, the histogram of the probability distribution of the instantaneous frequency of the analyzed signal (HPFD) was calculated after the Hilbert transform. The number of bins was calculated according to the following formula (Heald 1984):

$$M = \mathrm{int}\left[\frac{(x_{\max} - x_{\min})}{\left(\frac{5}{N}\right)^{1/5}}\right]$$

where X_{max} and X_{min} are the maximal and minimal values of the instantaneous frequency, N is the number of these samples.

The shape of the histograms does not allow for determining exactly the frequency component of interest. This was accomplished using power spectrum density of the signal (PSD).

The good resolution of the EEG frequency histogram makes it possible to determine a group of very close well-pronounced peaks in a given frequency band. To select the appropriate f_0 among them, several simple procedures are performed: (i) PSD is calculated and the highest peak within the group of frequencies is selected; (ii) the signal is demodulated and the curve A_t is inspected to check whether it wraps exactly the filtered narrow-band signal. Because the PSD resolution is lower than that of the histogram, the selected PSD peak may not coincide exactly to any of the groups of peaks from the histogram. Then (iii) another peak of PSD is selected and the step (ii) is repeated. The procedure iterates until the shape of A_t and envelope of the filtered signal coincide. If such a coincidence could not be achieved, this frequency is abandoned and a new frequency within the group is selected.

The PSD was evaluated through the Whelch scheme, i.e. by separating the signal into 256-samples overlapping segments and averaging their periodograms. The power (square) amplitudes were computed using the Hanning window. All these computations were accomplished by the [MATLAB 4.2] package on PC - "AT 386", 8Mb RAM.

Experimental set-up and data acquisition

The experimental set-up was designed to record EEG activity around the performance of goal-directed voluntary movement. The subject was instructed to select one of the three targets, to direct a light beam to it and to press a micro-switch when the target is reached. The movement was performed by the fingers of the right hand under conditions of free choice of the target and the instant of starting the movement. By using an electronic circuit, the moment of starting, reaching the target and returning to the starting position were recorded in parallel with the EEG.

Nine-channel EEG records, EOG and selected instances of the task performance were recorded (Nihon Kohden EEG-4314 F, Japan). AgCl EEG electrodes were placed according to the international 10-20 system in positions Fz, F3, F4, Cz, C3', C4', Pz, P3, P4 and filtered in the range 0.03-120 Hz. The sites C3' and C4' were chosen 1 cm anterior to the standard C3 and C4 positions. Eight-second records were fed off-line into computer through 10 bit ADC 256 samples/s incorporated in IBM PC I/O Board for digital collection (Kaminsky and Krekule 1994). The record consists of a segment 3 s before starting the movement and 5 s after it. The 10 subjects were paid volunteers, aged 19-35 years.

Results

Simulated signals

To illustrate schematically the ability of CD to detect the type of modulation, simulated frequency and amplitude modulated signals of 512 samples were generated with a sampling frequency of 250 Hz. Figure 1a shows a frequency modulated signal (FM) X_1. The PSD spectrum of this signal (Fig. 1b) contains multiple peaks, which are a result of the modulation, i.e. the so-

called side-band frequencies. In this case, the frequency of interest can easily be chosen to be the carrier frequency of the signal F_c. The curves of the A_t envelope and frequency deviation F_t follow the changes in both amplitude and frequency of the F_c component.

Figures 1c and 1d present a multicomponent signal as that in Figure 1a, where the same modulated signal X_1 is added to a sinusoidal signal X_2. This shows that although there is superposition with other frequency components, the CD method makes it possible to filter only the frequency of interest and demodulate it, revealing changes in the envelope A_t and frequency shifts F_t in time.

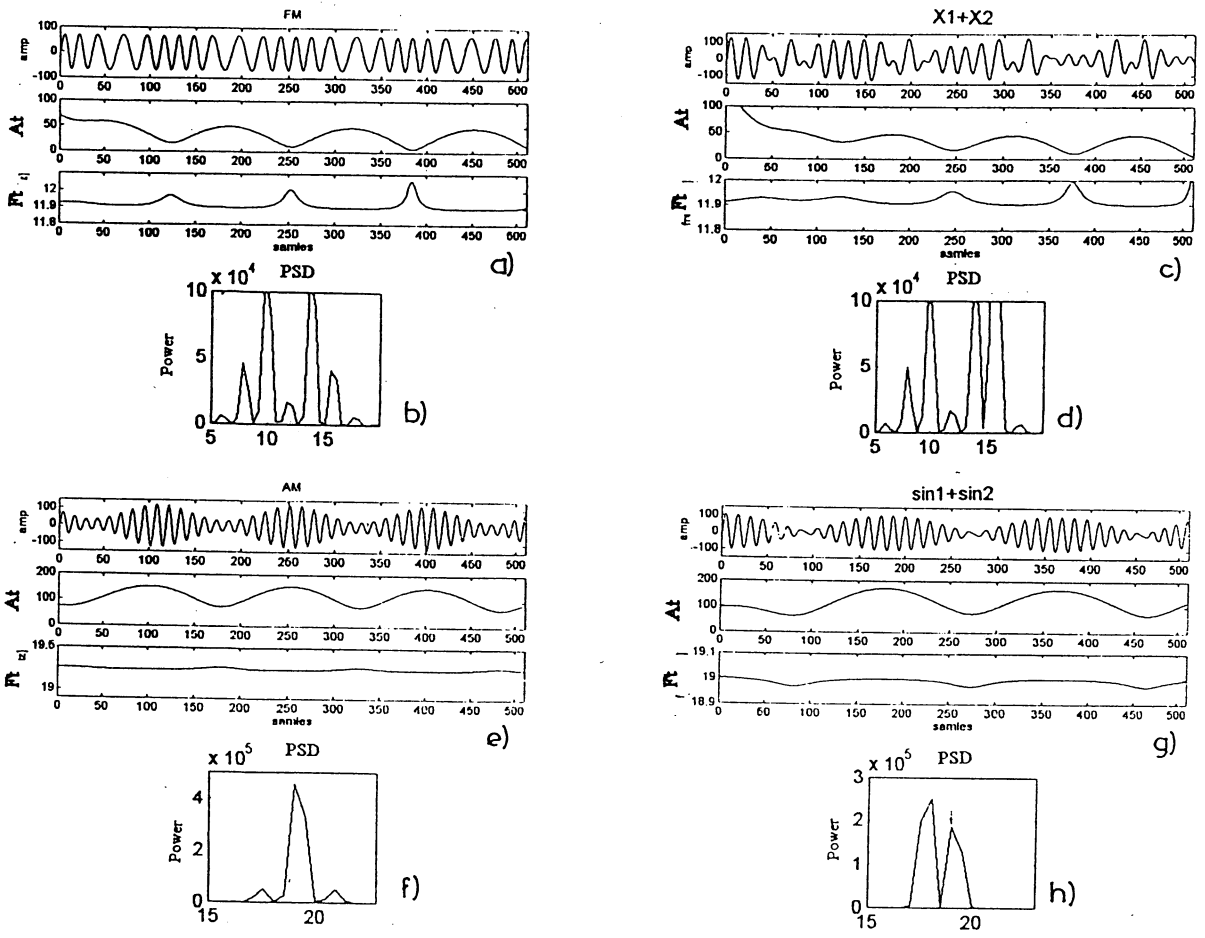

Fig. 1 (a) *FM simulated signal according to* $X_1(t) = A.sin[2\pi F_C.n.\Delta t + \varphi_C + k.sin(2\pi F_M.n.\Delta t + \varphi_M)]$, *where k is the index of the frequency modulation,* $F_C = 11.90$ *Hz, and* $F_M = 2$ *Hz, Envelope* A_t *and instantaneous frequency* F_t *obtained by demodulating of the carrier frequency* $F_C = 11.90$ *Hz.* **(b)** *PSD of the FM signal, the carrier frequency at 11.90 Hz and the side-band frequencies* $F_C + F_M$, $F_C - F_M$, $F_C + 2F_M$, $F_C - 2F_M$, $F_C + 3F_M$ $F_C - 3F_M$. **(c)** *The sum* $X_1 + X_2$ *of the FM signal* X_1 *and a sinusoidal signal* X_2 *according to* $X_2(t) = A.sin(2\pi f_1.n.\Delta t + \varphi_1)$, $f_1 = 15.63$ *Hz, envelope* A_t *and instantaneous frequency* F_t *of the demodulated signal for Fc.* **(d)** *PSD of the signal* $X_1 + X_2$. **(e)** *AM simulated signal according to* $X_3(t) = A[1 + m.sin(2\pi F_M.n.\Delta t + \varphi_M)].sin(2\pi F_C.n.\Delta t + \varphi_C)$, *where m is the depth of the modulation,* $F_C = 19.23$ *Hz,* $F_M = 2$ *Hz;* A_t *and* F_t *for demodulated signal.* **(f)** *PSD of the AM signal.* **(g)** *The sum of two very close sinusoidal signals with frequencies of 18.23 Hz and 19.23 Hz,* A_t *and* F_t *of the demodulated signal for* $F = 19.23$ *Hz.* **(h)** *PSD spectrum of the signal.*

In the case of amplitude modulation (AM) (Figs 1e, 1f), the complex demodulation of the carrier frequency is reflected only in the fluctuation of the envelope A_t. To illustrate how spindles of the sum of two very closely related frequencies (Fig. 1h) could be distinguished from the spindles of AM, see the graph in

Figure 1g. Besides the envelope curve, some small deflections are to be seen at the end of the spindle in the curve of the F_t, which reflects the reduction in frequency. This is not expressed in the AM signal.

EEG data

The analysis of three EEG records of one subject at positions Cz, C3' and C4' taken before, during and after the movement is illustrated. These sites cover the brain areas activated during performance of voluntary finger movements. Eight-second segments free of artifacts, according to the EOG, were selected.

The frequency histograms of the records are plotted in Figure 2 (upper panels). Many peaks in the histograms make it difficult to choose a single carrier frequency. According to our intentions to study the dynamic changes in the alpha, beta and gamma bands, we selected the most pronounced peaks: slow (7-10 Hz) and fast (11-14 Hz) alpha, $beta_1$ (15-20 Hz) and $beta_2$ (21-30 Hz), and gamma (31-46 Hz). Using PSD spectra, the frequency components of interest within these bands were located. Figure 2 (lower panels) shows the PSD of the selected records with the selected frequency components.

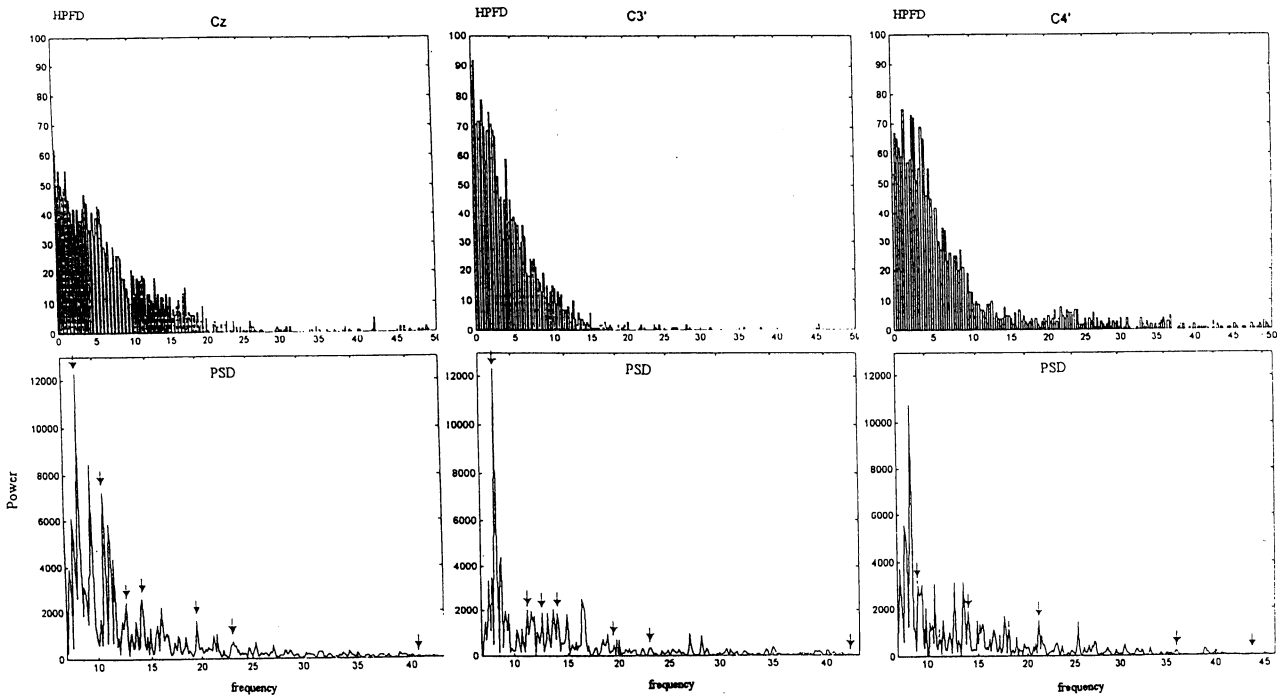

Fig. 2. *Histograms of the probability frequency distribution (HPFD) of the records Cz, C3', C4' (upper panels) and their PSD spectra (lower panels), respectively. The selected frequencies of interest are marked by arrows.*

The demodulation of frequencies giving their envelope A_t [AMP] and instantaneous frequency F_t [FREQ] curves are shown in Figure 3. The value of the chosen frequency is indicated at the left corner of the graphs. The phases of movement performance are marked below the respective columns as S (starting of movement), B (button pressing) and E (end of the movement).

The following rules were employed to detect the modulation and to relate it to the dynamic changes of the EEG. A decline of the envelope curve indicates the process of desynchronization, i.e. the rhythm is being suppressed. The fluctuation of A_t corresponding to a stable instantaneous frequency F_t is defined as amplitude modulation (AM). The rhythmical changes in both F_t and A_t suggest frequency modulation (FM). In segments where A_t and F_t remain regular without any fluctuations, the rhythm is considered to be stable and is presented as a linear process.

Some common tendencies in EEG at Cz (central) and C3' (contralateral) sites were observed. The slow alpha rhythm, whose amplitude and frequency

changes are important for distinguishing the movement phases (Pfurtscheller and Aranibar 1979), was first selected. For Cz and C3' it was located at 8.3 Hz and at 9.12 Hz for C4'. The results of the CD-estimation for records at Cz and C3' show a decrease of AM immediately before starting the movement in the interval 0.5 s before S and one second later for C4'. This suggests a blockade of the rhythm. The existence of AM for Cz, C3' and C4' could be expected for a longer period before S, if the sharp deflections in F_t are neglected. These could be due to breaks in the rhythm and not to frequency modulation, where the peaks in F_t are wider. Hence, the process of modulation precedes the process of desynchronization which originates first in C3', Cz and is propagated in C4' (ipsilateral) with a time delay of one second. Button pressing (B) is related to the activation of slow alpha rhythmicity.

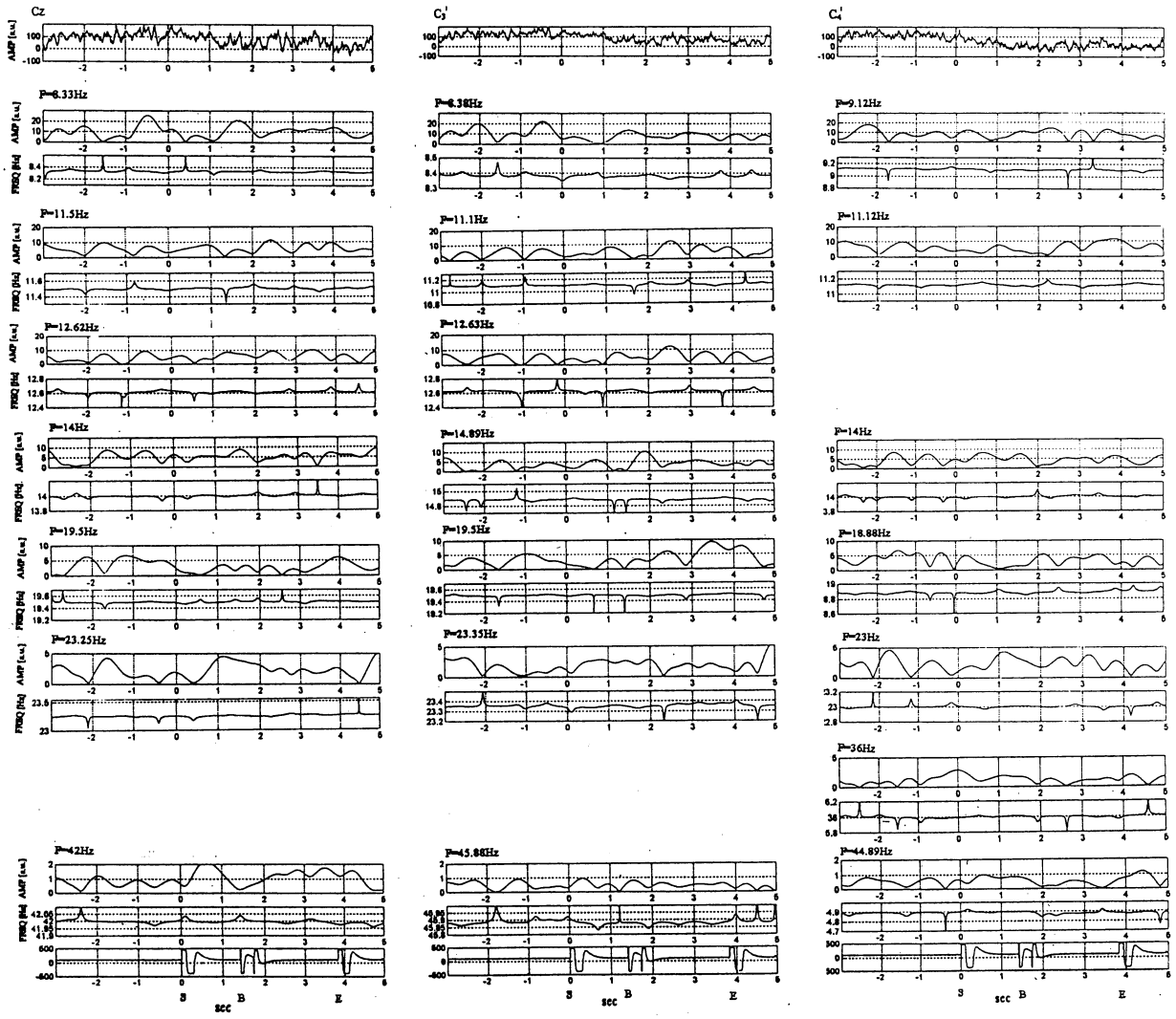

Fig. 3. *On the left: demodulation of the different frequency components of interest for Cz, envelope curve A_t denoted as AMP and instantaneous frequency of the demodulated component denoted as FREQ. In the middle: A_t and F_t of the demodulated frequency components for record C3', On the right: A_t and F_t of demodulated frequency components for record C4' (see text).*

The fast alpha range for two frequencies, 11.1 Hz and 12.6 Hz, is presented. The F_t curve of the 11.1 Hz is completely stable for both records Cz and C3' in the period of 1-2 s prior to button pressing. During this period, the A_t fluctuations suggest AM in Cz, which becomes attenuated when the subject presses the button.

A desynchronization of this rhythm first occurs around S and then around button pressing. A blockade of the rhythm originates in Cz and C3' around zero second (phase S) and later in C4' with a time delay of 0.5 s. For C4', the second suppression of the rhythm also follows after phase B with a time delay of 0.5 s. The activation of this rhythmicity and its modulation appear 1 s after phase B, i.e. one second later than those in slow alpha oscillation.

The fast alpha rhythm of 12.6 Hz was not present in C4'. The changes in the envelope curve for Cz and C3' suggest that a process of desynchronization starting around 0.5 s after S is involved. Both records are characterized by the generation of a stable rhythm of 12.6 Hz, 0.5 s immediately before pressing the button which persists for 0.5 s thereafter. An increase of the amplitude from 0.5 s after pressing the button to the end of the movement is observed.

The slow $beta_1$ rhythm is presented for a frequency of 14 Hz. A process of AM beginning 1 s before S at position Cz is propagated with a delay of one second at C3' and C4'. The AM is followed by a desynchronization with the same time delay. The phase B of the movement is characterized by stable parameters 0.5 s before B in Cz and 1 s after B in C3' and C4'. This rhythm is also characterized by a distinct increase of the envelope (activation) before and during phase B in lead C4'. A second desynchronization of the oscillation is seen 0.5 s after button pressing. To summarize, a process of AM, followed by a blockade of the rhythm appearing in the signals, which originate in Cz, one second later it continues in C3' and 1 s later is to be seen in C4'.

The fast $beta_2$ is presented for two frequencies of 19.5 Hz and 23.5 Hz. A process of desynchronization of the rhythm 19.5 Hz is observed, initiated 0.5 s before S for C3', immediately between 0-1 s for Cz and 0.5 s after S for C4'. A process of modulation is observed 1-2 s before S and during pressing of the button (B) in records Cz, then in C3' immediately after pressing (for 1.5-3 s) and in C4' one second after pressing the button (for 2.5-4 s). The behavior of the frequency component around 23.35 Hz is very interesting. Contrary to the results so far, the process of desynchronization is shifted one second before starting the movement. Activation of the rhythm is seen 1 s before and during button pressing. During this period, the F_t curve is flat and only very slight fluctuations of the envelope can be observed. It could be stated that in this movement phase, this rhythm exhibits completely stable parameters up to the end of the movement for Cz. The processes of modulation appear 1 s after B in leads C3' and C4'. In conclusion, this rhythm is activated immediately after starting of movement (S), and before button pressing (B). This process originates first in C3' and is then propagated to Cz and C4'.

The gamma bursts were also investigated in the range from 35 Hz to 46 Hz. The frequency component of interest 36 Hz was located only when recording from C4'. Activation of this rhythm is observed 1 s before starting movement (S). The rhythm of this frequency is stable and lasts 3 s, which includes the start (S) and button pressing (B). The changes in amplitude during this period suggest amplitude modulation. This modulation may be interpreted as activation of the rhythm. Diminishing of the amplitude outside this period reflects the instability of F_t. The second component within this range was 42 Hz for Cz, 45.88 Hz for C3' and 44.89 Hz for C4'. This rhythmicity is characteristic for activation of Cz and C4', where a large increase of amplitude at constant frequency could be seen 1 s before button pressing. At the moment of button pressing, a process of desynchronization begins for Cz and 1 s later for C4'. The deviation of the frequency in C3' diminishes 0.5 s after button pressing and suggests frequency modulation. The FM persists after termination of the movement.

On the basis of these results, it is possible to state that the process of desynchronization for the frequencies of interest in the range 8-14 Hz was found 0.5 s before the onset of movement for Cz and C3' and about 1 s later in C4'. An exception to this was the fast beta frequency of 23.5 Hz and gamma around 40 Hz, which became desynchronized 1.5 s before S, and were activated before and during pressing button. Another exception concerned the record at C4', where desynchronization of the slow alpha and fast $beta_2$ appeared again 1 s after S, before button pressing. Significant activation before and during the button pressing was observed in C4' for $beta_1$ (14 Hz), $beta_2$ (23.5 Hz) and gamma activity (40 Hz), as well as for fast alpha (12.6 Hz) and fast $beta_2$ (23.5 Hz) for Cz and C3'.

Discussion

The characteristic properties of the CD method to delineate the changes in amplitude and frequency shifts in time for non-stationary processes have been successfully applied to EEG records. The main result concerns the finding that modulation (mostly of amplitude) exists in scalp EEG activity which changes around the performance of a cognitive task. Using pass-band filtering, a decrease of alpha and beta activity

before voluntary movements and the recovery of post-movement beta has been already reported (Pfurtscheller and Klimesch 1992, Pfurtscheller *et al.* 1996). Additionally, using a unique spectra technique, bursts of beta activity have been found in some trials immediately after reduction of the alpha components (Mineva and Popivanov 1996). The present results extend these findings, revealing that these changes are due to the suppression of amplitude modulation in these frequency bands. Thus, the period of movement preparation is associated not only with the "event-related desynchronization" but also with a non-linear process of modulation which decreases before the movement. The additional contribution of CD analysis is that the modulation is pronounced for different aspects at different frequencies in a selected band. Thus, fast beta and gamma activity precedes by about 1 s that of low alpha activity and recovers earlier during the movement performance. In general, the results so far suggest that during the period of a complex movement task, the EEG modulation decreases (or disappears) and again reappears despite the fact that the task has not been completed. This could be due to the complicated fine goal-directed movement, where the subjective estimation of the end of the task seems to be the button pressing and not returning back to the start position.

The crucial problem in CD application to the EEG is to select the characteristic frequencies within a given frequency band. In this study, this difficulty was overcome by using the Hilbert transform, frequency histograms and power spectra. However, further extensive research is needed to test the many possible frequencies of relevance. In this sense, the generalization of our findings to all subjects and recording sites was beyond the scope of this paper. Further research is needed to select appropriate criteria for statistical estimation of the results bearing in mind intra- and inter-individual variability. The averaging of data between subjects could be the first step, but probably not sufficient because of the different individual strategy in task performance. Another difficulty proved to be the exact discrimination of the effect of summation of nearby frequencies from the frequency modulation. A study in this direction is in progress.

In conclusion, despite the difficulties in application and some hitherto unsolved problems, the technique of CD is promising in tracking the dynamics of EEG frequency components. The nonlinear dynamics of some frequencies and their changes in the course of time, detected *via* CD, are a useful complement to other linear methods widely employed so far for detecting various brain rhythms, their location and propagation.

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References

BLOOMFIELD P: Complex demodulation. In: *Fourier Analysis of Time Series: An Introduction*. John Wiley, New York, 1976, pp 118-150.

CHILDERS D, PAO M: Complex demodulation for transient wavelet detection and extraction. *IEEE Trans Audio Electroacoustics* **AU-20:** 295-308, 1972.

HAYANO J, ANDREW T, YAMADA A, MUKAI S, HORY R, ASAKAWA T, YOKOYAMA K, WATANABE Y, TAKATA K, FUJINAMI T: Continuous assessment of hemodynamic control by complex demodulation of cardiovascular variability. *Am J Physiol* **264**: H1229-H1238, 1993.

HAYANO J, ANDREW T, MUKAI S, OKADA A, WATANABE Y, TAKATA K, AND FUJINAMI T: Assessment of frequency shifts in R-R interval variability and respiration with complex demodulation. *J Appl Physiol* 77: 2879-2888, 1994.

HEALD MA: On choosing the bin width of a Gaussian histogram. *Am J Phys* **52:** 254-255, 1984.

KAMINSKY Y, KREKULE I: Universal multifunctional IBM PC I/O board for clinical examinations and experimental research in neuroscience. *Physiol Res* **43**: 193-199, 1994.

MINEVA A, POPIVANOV D: Method for single-trail readiness potential identification, based on singular spectrum analysis. *J Neurosci Meth* **68**: 91-99, 1996.

PFURTSCHELLER G, ARANIBAR A: Evaluation of event-related desynchronization (ERD) preceding and following voluntary self-paced movement. *Electroencephalogr Clin Neurophysiol* **46**: 138-146, 1979.

PFURTSCHELLER G, KLIMESCH W.: Functional topography during a visuoverbal judgment task studied with event-related desynchronization mapping. *J Clin Neurophysiol* **9** 120-131, 1992.

PFURTSCHELLER G, STANCAK JR, NEUPER C: Post-movement beta synchronization. A correlate of an idling motor area? *Electroencephalogr Clin Neurophysiol* **98**:281-293, 1996.

Reprint requests

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