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Investigation of coherence structure and EEG activity propagation during sleep

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Abstract. Overnight sleep EEG recorded from 21 derivations was studied for 7 subjects (4 normal and 3 depressive). The multichannel autoregressive model was fitted to all 21 channels simultaneously. Ordinary, multiple and partial coherencies and directed transfer function were estimated for sleep stages and wakefulness. Ordinary coherencies give rather trivial information that coherence decreases with the distance. Partial coherencies revealed specific structure to a large degree repeatable for studied subjects. Study of directed transfer function made possible the identification of main centres from which EEG activity is spreading during sleep. An EEG analysis, based on treating signals as a realization of one process and on simultaneous (not pair-wise) evaluation of time series, offers new possibilities in the investigation of synchronization and functional relations in brains.

Key words: multichannel AR model, overnight sleep analysis, partial coherencies, directed transfer function

Sleep studies were traditionally based on recording of one or two EEG channels plus two EOG and EMG channels. Technical development and progress in computer methods in the last few years have made possible the evaluation and mapping of EEG activity from a larger number of channels. Initial studies on EEG topography during wakefulness and sleep were reported by Buchsbaum et al. (1982), Eteventon and Guillon (1986) and Eteventon (1989). Zeitlhofer et al. (1993) studied sleep EEG for 18 channels for a group of 10 normal subjects. In their study the absolute and relative spectral power was determined in 13 frequency bands and topographical representation of results was given. In the investigation of brain functional dynamics the mutual relationships between brain regions are of primary importance. These relationships are reflected by covariance structure of signals, namely by correlations and coherencies. In sleep studies investigation of coherencies has been limited to two channels only (e.g. Armitage et al. 1993) and coherence between left and right hemisphere has been calculated. We have developed a method which describes functional relationships between brain regions by means of coherencies and Directed Transfer Function (DTF). The important feature of this method is the fact that brain signals are treated as realizations of one process and are evaluated simultaneously not pair-wise, as it was traditionally done. In our approach, a multichannel AR model was fitted to 21 channels of EEG and from model coefficients ordinary, multiple and partial coherencies were calculated. DTF, which gives information on spectral content and direction of EEG activity propagation was also determined.

Whole night polygraphic recording was performed in 4 healthy volunteers (3 males, 1female, aged 23-53 years) and 3 patients with Major Depression (2 males, 1 female aged 23-58 years), according to the DSM-III-R classification (American Psychiatric Association, 1987). Apart from the standard polysomnographic derivations (Rechtschaffen and Kales 1968), 21 channels of EEG according to the 10-20 standard and A1 and A2 derivations were recorded. The data were recorded with respect to linked ears electrode and downfiltered by an antialiasing filter in the band 0.16-40 Hz. Sampling frequency was 102.4 Hz. Data were stored on 650MB MO disks. Visual scoring of sleep was performed by 3 independent electroencephalographers, from a 20" monitor, according to the common standard (Rechtschaffen and Kales 1968). Further analysis was performed on the data epochs which were unanimously classified by all three experts. Artifacts were visually analysed and rejected in successive 2.5 s segments. The problem of the reference electrode merits attention. Common average reference recommended by some authors (e.g. Lehmann et al. 1986) is not appropriate in our case. According to Pfurtscheller (1981) this kind of reference is ill-suited when the signals reveal a high degree of coherence and high similarity. Fein et al. (1988) found that common reference coherence data are confounded by power and phase effects; therefore we have used linked ears reference.

The method of analysis was based on the multichannel AR model which is a well known method of stochastic signals evaluation (Priestley 1981). Its superiority over FFT has been demonstrated (e.g. Isaksson et al. (1981), Blinowska et al. (1981), Blinowska (1994)), nevertheless AR is seldom used in its multichannel form for more than 2 channels. The algorithm of multichannel AR model calculation was elaborated by Franaszczuk et al. (1985). In the following only the basic features of the method will be sketched.

The multichannel AR model can be expressed in the form:

$$\sum_{j=0}^{p} \hat{A}_j x_{t-j} = e_t \qquad (1)$$

where $x_t = (x_{1,t}, x_{2,t}, ..., x_{k,t})$is the vector of a k-channel process and $e_t = (e_{1,t}, e_{2,t}, ..., e_{k,t})$ is the vector of a multivariate, zero mean uncorrelated noise process, $\hat{A}_1$, $\hat{A}_2$, ..., $\hat{A}_p$ are kxk matrices of model coefficients, t denotes time. Eq. 1 means that a sample x_t of the signal is expressed by the weighted sum of certain numbers of the preceding samples plus a noise component.

Transforming eq. 1 to the frequency domain we get:

$$\hat{X}(f) = \hat{H}(f)\hat{E}(f) \quad (2)$$

where

$$\hat{H}(f) = \left[\sum_j \hat{A}\exp(-2\pi ijf\Delta t)\right]^{-1} \quad (3)$$

is a multichannel transfer function. The AR model is a "black box" model, i.e. it can be considered as a sort of filter with a white noise (e_t) as an input and EEG series (x_t) at the output (Fig. 1). The AR model extracts frequency-specific information about a signal from the noise; this information is contained in a transfer function. The transfer function can be found from AR model coefficients which are calculated using well known procedures, e.g. Marple (1987).

The spectral matrix is obtained from the formula:

$$\hat{S}(f) = \hat{H}(f)\, \hat{V}_e\, \hat{H}^{*}(f) \quad (4)$$

* means transposition and complex conjugation; $\hat{V}_e$ the spectral matrix of input white noise processes.

In eq. 4 $\hat{H}(f)$ describes spectral properties of signal and $\hat{V}_e$ its frequency-independent variance. The dimension of $\hat{S}(f)$ is kxk (k - number of channels). In multichannel model spectral matrix contains autospectra of all channels and all cross-spectra.

Let us denote its element by $S_{mj}(f)$ and by $M_{ij}(f)$ its minor corresponding to element $S_{mj}(f)$, then partial coherence will be expressed by the formula:

$$\chi_{mj}(f) = \frac{M_{mj}(f)}{\sqrt{M_{jj}M_{mm}(f)}} \quad (5)$$

and multiple coherence by:

$$\mu_m(f) = \frac{1 - \det \hat{S}(f)}{\sqrt{S_{mm}(f)M_{mm}(f)}} \quad (6)$$

Multiple coherence is a measure in the frequency domain of the common variance of a given channel with all other channels of the set. A high value of multiple coherence tells us that a given channel is strongly interconnected with all other channels of the set; it also means that our model accounts well for all the variance of the system. Partial coherence describes the joint variance of two channels, after the influence of all other signals of the system has been removed. This means that partial coherence describes only direct connection between signals. Contrary to ordinary coherence, common driving of two channels A and B by a third one will not contribute to the partial coherence between A and B, therefore a much clearer pattern of the mutual relationships between signals can be obtained.

The above described multichannel AR model was extended by the introduction of an estimator called Directed Transfer Function (Kamiński and Blinowska 1991). We have made use of the fact that the transfer function (eq. 3) is asymmetric and information about the directions of signals propaga-

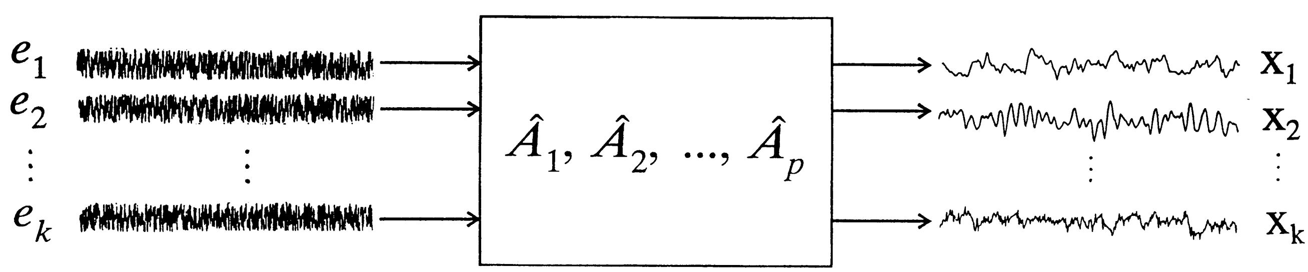


Fig. 1. A diagram of multichannel AR model.

tion is contained in it. Directed Transfer Function of the system was defined as:

$$\gamma_{ij}^2(f) = \frac{|H_{ij}(f)|^2}{\sum_{m=1}^{k} |H_{im}(f)|^2} \qquad (7)$$

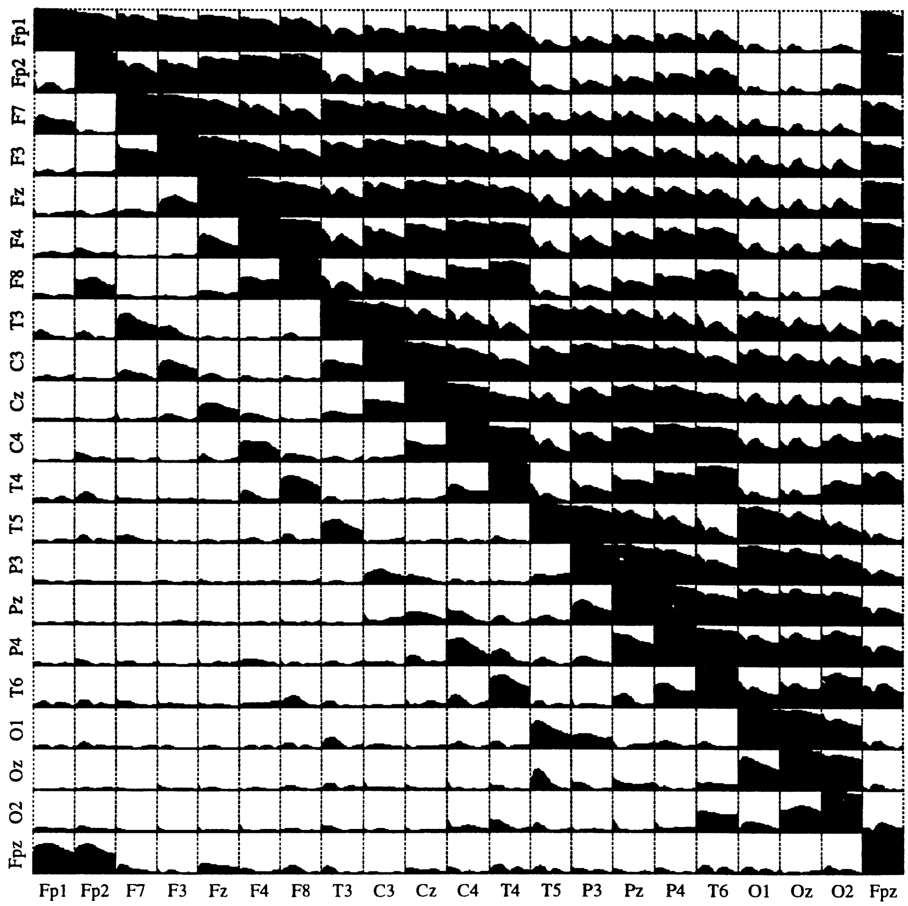
where $H_{ij}(f)$ is an element of $\hat{H}(f)$ matrix $H_{ij} \neq H_{ji}$. The squared sum of all elements of the relevant row in the denominator of eq. 7 normalizes $\gamma_{ij}(f)$ in the range [0,1]. $\gamma_{ij}(f)$ is a frequency dependent estimate of activity flow from channel j to channel i. DTF describes propagation between channels, furnishing at the same time information about their directions and spectral characteristics. This makes possible the identification of a situation where different frequency components are propagating in different ways.

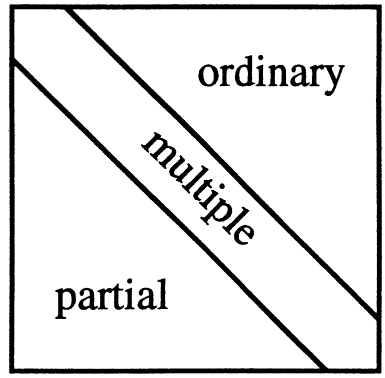
The properties of the DTF have been tested by means of simulations (Kamiński and Blinowska 1991). They revealed that DTF is very sensitive i.e., a shift by one or two samples between signals gives a very distinct effect. DTF is robust with respect to noise; the addition of noise even of an amplitude equal to the signal has practically no influence on the results. DTF function and coherencies determined in the framework of the AR model were used in clinical and experimental studies, for determination of epileptic foci (Franaszczuk et al. 1994), for estimation of brain activity propagation in the perceiving cat (Bekisz and Wróbel 1993), and for evaluation of EEG activity spread during various behavioural states in the chronic animal (Korzeniewska and Kasicki 1993).

Before the application of the AR model artifacts were eliminated by rejecting 2.5 s. blocks of data. For analysis only continuous artifact-free epochs were used. The AR model was fitted to data records of 10 s durations. The model order was found for each record by means of Akaike's (1974) criterion. Then power spectra, ordinary, partial and multiple coherencies and DTF functions were calculated in the frequency range 0-30 Hz for all the channels. Also matrix of residual noise was estimated in order to check the goodness of fit of the model. The number of records processed depended on the duration of artifact-free epochs. For sleep stages 2 and 3 it was possible to find epochs without artifacts lasting up to about 10 min. For wakefulness state and REM these epochs were considerably shorter. The abundance of information contained in the processed data was very high, therefore some kind of results compression was needed. The coherence functions and DTFs belonging to the same artifact-free epochs were averaged. For sleep stages 2 and 3 the number of averaged 10 s epochs was usually around 40, for stage 1, stage 4 and REM around 10.

The results were presented in the form of frequency dependent plots and also in the form of bars or arrows (for DTF) showing propagation of EEG activity for different stages in the conventional frequency bands. In Fig. 2 a typical output of coherence analysis is shown. Multiple coherencies have very high amplitudes for all derivations and the whole frequency range which means that the system is strongly interconnected. A pattern of ordinary coherencies looks very similar for all electrodes during all sleep stages and for healthy as well as for depressed patients. Ordinary coherencies bring very little information. They fall monotonically with the distance, which is rather a trivial observation. Partial coherencies are much more informative. They give a distinct pattern repeatable for all normal subjects and to some degree also for the depressed. Typically coherencies front-back were higher than left-right. The coupling between hemispheres was especially low for depressed patients. Since this work has a methodical character the evaluation of differences in coherence pattern for different stages and groups of subjects will be discussed elsewhere.

Directed transfer functions give an abundance of information. In order to present spectral features of EEG propagation we have integrated DTFs in four frequency bands (1-7 Hz, 7-12 Hz, 12-15 Hz, 15-30 Hz) and we have presented activity flows by means of arrows (Fig. 3). Intensities of flows were illustrated by shades of grey. The repeatability of averaged estimates was good when the number of





Location of coherencies on the graph

Fig. 2. Typical output of coherence analysis for normal subject sleep stage 2. Multiple coherencies in the boxes on the diagonal, ordinary coherencies above diagonal, partial coherencies under diagonal. Coherencies between EEG signals from relevant derivations are shown at the intersections of corresponding rows and columns. The frequency scale in each box from 0 to 30 Hz.

averages was above 10. If we take into account single epochs then the pattern of flows differs. Analysis of sleep EEG based on averaged DTF indicates that the predominant centres of activity are similar for all subjects, healthy and depressed. Study of DTF suggests the hypothesis of two sites connected with EEG propagation, the sources seem to be located mainly in both frontal lobes and in the vicinity of P3 and P4 (or O1, O2 for some subjects). The study of single epochs shows that these centres are not active simultaneously, but that switching between them occurs. The investigation of the dynamic pattern of EEG propagation is in progress; perhaps it will require the use of shorter analysis epochs and special kinds of presentation. We have already observed for the transition between wakefulness and sleep the switching of EEG activity sources between frontal and posterior regions of the head (Blinowska et al.1994). It seems that the above - mentioned two sites are predominantly active also during whole night sleep.

A few studies of multichannel sleep EEG (mentioned in Introduction) were limited to the mapping of spectral content in traditional frequency bands. No estimation of covariance structure of signals was undertaken. In the work of Armitage et al. (1993) inter- hemispheric coherence was estimated for two homologous channels. The authors found smaller inter-hemispheric coherence for depressed patients in comparison to normals which agrees with our findings. Since we have evaluated 21 channels we were able to compare inter- with intra-hemispheric coherence, finding that the first one was considerably higher for all subjects. This observation corre-

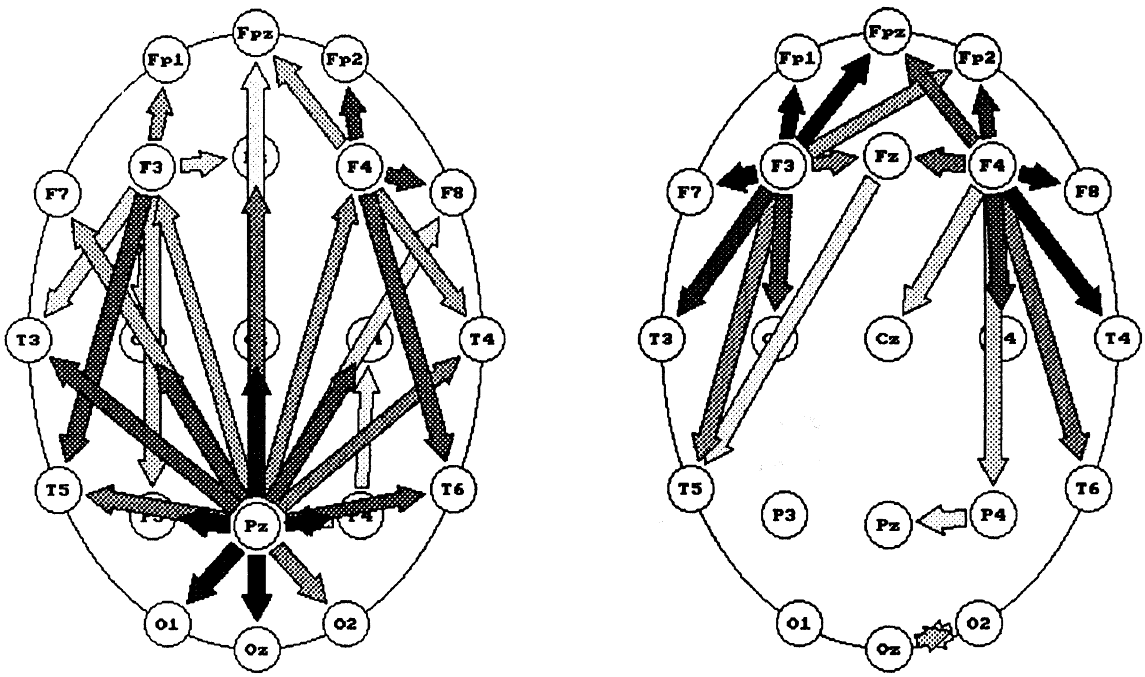


Fig. 3. An example of presentation of EEG activity flow estimated by means of DTF function. Sleep stage 2, frequency range 7-12 Hz; left, normal; right, depressed patient.

sponds well with the results of Tucker et al. (1986) who calculated multiple and partial coherencies for 8 channels of spontaneous awake EEG. However, the usual approach is still based on the estimation of ordinary coherencies. The information relying only on ordinary coherence may be seriously misleading, if the influence of other channels of the system is not accounted for. Thatcher et al. (1986) studied ordinary coherence in children. In order to distinguish the influence of common feeding on the coherence between two sites they used bivariate polynomial regression analysis. However in performing regression one has to decide which variables (coherencies) to take as dependent and which as independent variables. In this way the results are biased by initial assumptions. By using partial coherencies instead of ordinary coherencies the effect of common feeding is automatically eliminated since partial coherencies give intrinsic relationships between given two channels and eliminate the possible influence of all other channels.

An important aspect of this study was that in the framework of the AR model a method was elaborated which makes possible the distinction of direct and indirect connections and an estimation of the direction of EEG activity propagation. Usually the studies of coherencies are limited to ordinary coherencies, which often give vague information. The regression procedures applied by some authors on ordinary coherence only partly solve the above - mentioned problem. In order to track intrinsic relationships between signals they have to be treated as a realization of one process as is the case in our approach. Bullock (1993), recognizing the importance of coherence for study of brain processes, especially synchronization, emphasizes the serious limitations of ordinary coherence; namely it is not possible to distinguish, "(1) that both loci have a component of the energy at that frequency following a common driver, or (2) that one of the loci drives the other". It seems that methods elaborated by us may help in resolving both of these problems, (1) by means of partial coherence and (2) by means of DTF.

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