Development of relative power contribution ratio of the EEG in normal children: a multivariate autoregressive modeling approach

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Abstract

The relative power contribution ratio using a multivariate autoregressive model was applied to determine the spread of delta, theta, alpha and beta activity over the scalp in childhood. EEGs of 264 normal healthy subjects from 3 to 26 years were recorded from Fp1, Fp2, C3, C4, O1 and O2 with linked ears during the resting relaxed state with eyes closed. After selecting the epoch to remove artifacts, the relative power contribution ratio at each frequency band was calculated from the digitized EEG. The most noticeable developmental change was seen in the alpha frequency, where the relative power contribution ratio from its own area decreased significantly with age, and ratios from the other areas increased significantly. The change was larger at the frontal and smaller at the occipital region. Consequently, the occipital alpha wave was stable after 3 years of age. Developmental change at beta frequency was similar to alpha activity, but the number of components with significant change was smaller at delta and theta frequencies. Thus the relative power contribution of the EEG enabled us to observe how relationships among each location of EEG matured.

Keywords: Relative power contribution; Multivariate autoregressive model; EEG source localization; EEG band power; EEG maturation

1. Introduction

Alpha rhythm, observed in the occipital area of an adult lying quietly with eyes closed, has been studied actively since it was initially noted by Hans Berger in 1929. Its mutual relationship between electrode locations has also been extensively studied (Markand, 1990). However, these studies were mostly on 2-dimensional relationships and by potential mapping (Banquet, 1983; Thatcher et al., 1986, 1987; Ozaki and Suzuki, 1987).

Akaike’s relative power contribution ratio, based on a multivariate autoregressive model (Akaike and Nakagawa, 1988), is a dynamic multi-dimensional analysis method for detecting multiple relations. This method was available to indicate interactions and possible causal relationships between many locations of the EEG. Inouye et al. (1986) used the relative power contribution analysis (RPCA) to determine the source of alpha activity on the adult EEG. However, only a few reports are available on multi-dimensional relationships and their direction in childhood.

In the present study, the RPCA method was used on normal children’s EEGs to investigate developmental changes in the relationship between electrode locations at delta, theta, alpha and beta frequencies.

2. Methods and materials

2.1. Subjects

EEGs were obtained from 244 normal healthy children (male 133, female 131), ranging in age from 3 to 15 years, and 20 healthy adults aged 22–26 years – each 20 children (male 10, female 10) aged 3–12 years, 14 children (male 7, female 7) aged 13 years, and 15 children aged 14 and 15 years. They had: (1) no history of disease of the central nervous system, (2) no head injury with cerebral symptoms, (3) no convulsions, (4) no obvious mental disease, and (5) no abnormal EEG clinically.

2.2. Methods

Recordings were obtained from all subjects in a prone position on a bed with their eyes closed. EEGs were
recorded (Type 4217 or 5210s, Nihon Kohden, Tokyo, Japan: time constant = 0.3 sec, calibration of 50 $\mu$V = 5 mm) from 6 electrodes placed at Fp1, Fp2, C3, C4, O1 and O2 (10–20 international system), referenced to linked ears. The EEG signals were low-passed filtered with an anti-aliasing filter (40 Hz cut-off, down 24 dB at 50 Hz). It was observed that the children were not drowsy during the study. Six-channel EEGs were recorded on paper and on magnetic tape (R-280, TEAC Co. Ltd., Tokyo, Japan) connected to a minicomputer (Panafacom U-1200, Fujitsu, Tokyo, Japan). The EEG was reviewed off-line and data were digitized at a sampling interval of 20 msec for 10.24 sec. One artifact-free 6-channel epoch was obtained for each subject.

Relative power contribution ratios from 6 regions utilizing a multivariate autoregressive (AR) model were calculated with a minicomputer (Fig. 1).

The relative power contribution ratios at delta (1–3.5 Hz), theta (3.5–7.5 Hz), alpha (7.5–12.5 Hz) and beta (12.5–25 Hz) frequencies were investigated at each age. The degree of contribution to the whole frequency range, expressed in percentages, was calculated by Eq. (8) in the Appendix.

Developmental change was regarded as significant when $P$ values of simple linear regression analysis between ages and relative power contribution ratios were less than 0.05.

3. Results

Fig. 2 shows examples of relative power contribution to the C3 location in a 4-, a 9- and a 12-year-old child. The contribution ratios from all 6 locations to a certain area at 0–25 Hz are shown by corresponding curves in the figure (power contribution spectrum). Inouye et al. (1986) divided the relative power contribution ratio into that originating in its own area (e.g., ratio from Fp1 to Fp1) as "endogenous activity," and the other as "exogenous activity." Exogenous activity was paltry in younger children. In most older cases, curves were observed to peak at alpha frequency. And this exogenous activity at alpha frequency was larger than exogenous activities at other frequencies, as presented in the 12-year-old case in Fig. 2. The means of twenty 12-year-old children at alpha frequency are shown in Fig. 3 in a radar chart. The figure shows how power estimated from the recording at one area is contributed by all 6 areas. Maximum scale is 30%, and it is drawn as 30% if the ratio is larger than 30%. The larger the exogenous component, the greater was the area enclosed by lines. Most subjects at all ages had large exogenous alpha activity in the frontal area, particularly from the occipital region of the same side.

Fig. 4 shows change with age, of the relative power contribution ratios from each of the 6 electrode locations.
to Fp1 at alpha frequency. Endogenous activity decreased with age in all locations, while exogenous activity increased or did not change.

To investigate the significance of these changes, Pearson’s correlation coefficients between ages and relative power contribution ratios were calculated (Table 1).

3.1. Delta rhythm

Components from Fp1 to Fp2 (Fp1 → Fp2), C3 → C4, and O1 → O2 decreased significantly with age, and C3 → Fp1, C4 → Fp2 and O1 → C3 increased significantly.

3.2. Theta rhythm

Components of Fp1 → Fp2, C3 → C4, O1 → O2, O1 → O2 and O2 → O2 decreased significantly with age, and Fp1 → C4, Fp1 → O2, C3 → Fp1, C3 → O1, C4 → Fp2, C4 → C4 and C4 → O2 increased significantly.

3.3. Alpha rhythm

All endogenous components decreased significantly. All exogenous components excluding Fp1 → C3, Fp1 → C4, Fp1 → O1, Fp2 → Fp1, Fp2 → C3, Fp2 → C4, Fp2 → O1, Fp2 → O2 and C3 → C4 increased significantly with age.

The absolute value of Pearson’s correlation coefficients are largest for relative power contributions from all locations to the frontal area at alpha frequency.

3.4. Beta rhythm

Endogenous components of Fp1 and Fp2, and exogenous components of Fp1 → Fp2, decreased significantly. All contributions from occipital to central areas, from central and occipital to bilateral frontal poles excluding...
4. Discussion

The development of EEG at delta, theta, alpha and beta frequencies has been studied extensively (John et al., 1980; Ogawa et al., 1984; Matsuura et al., 1985; Gasser et al., 1988a,b; Alvarez Amador et al., 1989). However, only a few reports are available on multi-dimensional relationships in childhood.

Gasser et al. (1988a), in a study on EEG of 158 normal children and of adolescents aged 6–17 years, found that (1) the power of all recorded areas at delta, theta and alpha frequencies decreases with age, especially in the occipital area, (2) alpha2 power at posterior derivations increases up to 13 years of age and then decreases, (3) the power of beta rhythm decreases moderately with age, and

![Graphs showing relative power contributions from each electrode location to Fp1 at alpha frequency.](image-url)

Fig. 4. The relative power contributions from each 6 electrode locations to the Fp1 are plotted for all subjects, by age, at alpha frequency. Correlation lines between age and the relative power contribution ratios are shown.
(4) increases and decreases for the alpha and theta bands are complementary and level off at about the age of 14 for relative power.

Ogawa et al. (1984) examined the waking EEG of 150 normal children aged 20 days to 15 years using an autoregressive model, and found the relative power of the delta waves to decrease with age, alpha and beta power to increase, and theta power to increase up to 2-4 years of age followed by a decrease.

Many reports showed that decreases in delta and theta rhythm and increases in alpha rhythm apparently occur together, and variation in beta frequency was not remarkable (John et al., 1980; Ogawa et al., 1984; Gasser et al., 1988a).

The relationship between the electrode locations for each frequency band has been reported (Suzuki, 1974; Banquet, 1983; Petsche et al., 1984; Inouye et al., 1986; Thatcher et al., 1986, 1987; Hogan and Fitzpatrick, 1987; Table 1

Simple linear regression analysis at each frequency band. Figures indicate Pearson's correlation coefficient between the relative power contribution ratio and ages

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* P < 0.05.
** P < 0.005.
*** P < 0.0005.
Ozaki and Suzuki, 1987), but few papers investigated their developmental change.

The spread of alpha activity was studied with various methods (Suzuki, 1974; Inouye et al., 1986; Hogan and Fitzpatrick, 1987; Ozaki and Suzuki, 1987).

Many hypotheses concerning the generators of alpha rhythm have been proposed (Hogan and Fitzpatrick, 1987; Başar and Bullock, 1992). A cortical source in the occipital lobe is considered one of the principal generators of alpha rhythms. On the other hand, some consider thalamic pacemakers to be involved in the origin of alpha rhythm. However, no definite mechanism for alpha rhythm has been established, to say nothing of delta, theta and beta rhythms.

Akaike’s relative power contribution method based on the multivariate autoregressive model (Akaike and Nakagawa, 1988) is a dynamic multi-dimensional analysis method, which indicates interactions and possible causal relationships between many locations of the EEG.

Inouye et al. (1986) applied the relative power contribution analysis to the adult EEG and found more endogenous components in the anterior region and more exogenous components in the posterior area. In their investigation many exogenous components at various frequencies were observed in frontal and central areas, and alpha waves were shown to originate in the occipital area and to become widely distributed.

In the present study, the RPCA method was used on normal children’s EEGs to investigate developmental change in the relationship between electrode locations at delta, theta, alpha and beta frequencies.

Relative power contribution in normal children at alpha frequency was similar to that observed by Inouye et al. (1986) in normal young adult data. However, younger children had a larger endogenous power ratio in each area, particularly the frontal pole, which increased gradually with age. Exogenous power from other areas was thus large at the frontal pole and endogenous power was large in central and occipital regions in childhood. These results indicate that alpha rhythms in the occipital area are stable and are involved in modifying the EEG activity in other areas with development.

Delta and theta rhythms showed small developmental changes in this study. In early childhood, the theta rhythm is dominant and considered a precursor of the alpha rhythm (Markand, 1990). Data before 3 years of age would be necessary for determining a change from theta to alpha dominant rhythms.

We divided each band by threshold of frequency and examined development in that band area. Since the dominant frequency of the EEG varied with development during childhood, this method may not be suitable. However, in spite of demarcation in frequency, significant changes with development were denoted by simple linear regression analysis.

At beta frequency, the development was similar to maturation of the alpha waves, with the exception that only frontal components decreased significantly and only components from the occipital region increased significantly.

In this study we have found Akaike’s relative power contribution method to provide considerable insight into the source of origin of the frequency components of the EEG at each of the 6 electrode placements in children. Additionally, with this maturation, of the relative power contributions at each location, from all 6 locations in each frequency band. Changes in the relative power contributions in the alpha and beta bands were found to be most significant with age.

### Appendix A

**Estimation of relative power contribution using a multivariate autoregressive model**

Consider the k-dimensional stationary time series $X(s) = (x_1(s), x_2(s), ..., x_k(s))^\top$ where $\top$ denotes transpose. It is assumed that $x_i(s)$ represents deviation from the mean value. Autoregressive representation is given by (1),

$$X(s) = \sum_{m=1}^{M} A(m) X(s-m) + U(s)$$

(1)

where $U(s) = (u_1(s), u_2(s), ..., u_k(s))^\top$ is a k-dimensional white noise with zero mean vector and covariance matrix $\Sigma$. The $k \times k$ matrix $A(m)$ denotes the matrix of autoregressive coefficients.

Let $A_{ij}(m)$ denote the $(i,j)$-th element of $A(m)$. Then (1) can be expressed as (2).

$$X_i(s) = \sum_{m=1}^{M} \sum_{j=1}^{k} A_{ij}(m) X_j(s-m) + U_i(s)$$

(2)

Here, $A_{ij}(m)$ denotes the impulse response function from the input $x_j(s)$ to output $x_i(s)$. $M$ that minimizes Akaike’s information criterion (AIC) is determined and is defined as (3).

$$AIC = -2 \ln(\text{maximum likelihood}) + 2(\text{number of parameters})$$

(3)

The frequency response function $a_{ij}(f)$ of $x_i(s)$ to input $x_j(s)$ is given by (4).

$$a_{ij}(f) = \sum_{m=1}^{M} a_{ij}(m) \exp(-i 2\pi f m)$$

(4)

Once the AR model is fitted, the power spectral density function of each variable $x_i(s)$ is given by (5).

$$P_i(f) = \sum_{j=1}^{k} |b_{ij}(f)|^2 P_{x_j}(f)$$

(5)

where $b_{ij}(f)$ is (6),

$$b_{ij}(f) = \left[ I - \sum_{m=1}^{M} a_{ij}(m) \exp(-i 2\pi f m) \right]^{-1}$$

(6)
where $I$ denotes a $k \times k$ identity matrix. $q_{ij}(f)$ expressed as (7)

$$q_{ij}(f) = |b_{ij}(f)|^2 p_{ui}(f)$$

(7)

represents the contribution of $u_j(s)$ to the power spectral density of $x_i(s)$ at frequency $f$. Accordingly the relative power contribution is given by (8) (Akaike and Nakagawa, 1988).

$$r_{ij}(f) = \frac{q_{ij}(f)}{p_{ij}(f)}$$

(8)

References


