

The development of auditory evoked dipole source activity from childhood to adulthood

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Abstract

Objective: Multi-channel recordings show that observed developmental changes of late auditory evoked potentials (LAEP) depend on the location of the scalp electrode. These findings suggest that different LAEP generators have a distinct developmental course. The goal of this study was to investigate the maturational process of cortical LAEP generators.

Methods: Eighty-seven healthy children and adolescents with normal hearing, ages 5–16 years, and 21 adults, ages 20–30 years, participated in the study. Pure tone LAEP were recorded from 21 derivations. Dipole source analysis was performed by means of brain electric source analysis (BESA). Peak latencies and amplitudes of dipole source activity were estimated.

Results: While the number, location, and direction of dipole sources were similar in children and adults, the course of their activity differed greatly. The latencies shortened and the amplitudes decreased during development. In adolescence a new component appeared in the activity of the tangential dipole, which reflects the generators in the supra-temporal plane. The variability of parameters was greater in children than in adults.

Conclusions: Since the dipole source activity of LAEP in childhood differs considerably from that in adulthood, dipole source analysis could be a useful tool for studying both normal and disturbed maturation of the auditory perceptual function. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

Keywords: Event-related potential; Late auditory evoked potential; Dipole source analysis; Development

1. Introduction

Late auditory evoked potentials (LAEP) represent auditory processing in the cerebral cortex. Penfield and Jasper (1954) first localized the auditory cortex in the superior temporal gyrus by means of direct cortical stimulation. Celesia and Puletti (1969) confirmed this localization of auditory function by recording LAEP on the cortical surface.

LAEP are composed of multiple components. The best studied component is the N1. Neurophysiological studies after temporal lobe lesions have detected generators of N1 in the auditory superior temporal cortex (Kileny et al., 1987; Näätänen and Picton, 1987). Neuromagnetic dipole source analyses confirmed the origin of N1 in this area (Hari et al., 1980; Pantev et al., 1988, 1995; Kuriki et al., 1995). Neuromagnetic studies combined with MRI scans located the N1m sources in the depth of the Sylvian fissure, 2 cm poster-

ior to the point where the central sulcus and Sylvian fissure cross (Huotilainen et al., 1998). These findings demonstrate that the source extends beyond Heschl's gyrus over the planum temporale. In women the N1m sources are symmetrical, whereas in men the left hemispheric N1m source is about 1 cm posterior to that on the right side (Ohtomo et al., 1998). Lütkenhöner and Steinsträter (1998) studied a single subject extensively using high-precision neuromagnetic technique and 3 D MRI. They were able to register differences in source location that were less than 1 mm. The dipole moment estimation over time demonstrated a current flow of N1m generators into the cortex. These results indicate that multiple N1m generators exist, mainly in the planum temporale. The authors suggest that these generators correspond to the tonotopic fields of the auditory cortex.

Different subcomponents of the N1 have been described (Näätänen and Picton, 1987; McEvoy et al., 1997). Intracerebral recordings in humans suggest that the first subcomponent, which peaks at 60–75 ms, is generated in the postero-lateral part of Heschl's gyrus, and the second component, which peaks around 100 ms, mainly in the planum tempor-

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ale and less in the lateral part of Heschl's gyrus (Liégeois-Chauvel et al., 1994).

The generator of peak P2m was found anterior to the source of peak N1m. This location is equivalent to Heschl's gyrus (Lütkenhöner and Steinsträter, 1998).

The most commonly used technique to distinguish certain components of scalp-recorded LAEP in patients is brain electric source analysis (BESA). Based on spatio-temporal multiple dipole modelling, BESA allows evaluation of the activation of specific cortical areas and the interactions among several cerebral regions (Scherg, 1990). However, the head model used by BESA is a considerable simplification of the true situation. A simplified volume conductor model consisting of 3 or 4 homogeneous concentric spheres (brain, cerebrospinal fluid, skull, scalp) is applied. Moreover, BESA postulates that each source is stationary as regards location and orientation over the period of analysis, although movements of N1m sources have been described (Kuriki et al., 1995; Lütkenhöner and Steinsträter, 1998). Due to limited spatial resolution of BESA a single dipole is located in the centre of simultaneously active areas. All in all, BESA provides more information about the temporal sequence but less topographic information on the overlapping cerebral activities that underlie the scalp-recorded auditory evoked potential.

With BESA the generators of LAEP are best characterized as two dipoles per hemisphere: a tangential and a radial dipole localized in the temporal lobe (Scherg and von Cramon, 1990; Hegerl et al., 1994). The tangential dipole sources mainly represent the activity of the LAEP complex recorded on fronto-central sites. Scherg et al. (1989) separated the tangential dipole into two components that generate the N1 and the sustained potential, respectively. The radial dipole source radiates to the temporal area and may be equivalent to the T complex (Giard et al., 1994). The T complex is a bilateral, negative component recorded at temporal sites (Tonnquist-Uhlén, 1996). It is assumed that the tangential dipole represents the activity in the depth of the Sylvian fissure (planum temporale, Heschl's gyrus) and the radial dipole, the activity in the secondary auditory areas at lateral regions of the upper temporal lobe (Picton et al., 1999). Additional frontal sources were observed when the subjects attended to the stimuli (Dien et al., 1997; Picton et al., 1999). The location of auditory areas by dipole source analysis of scalp EEG corresponds to findings in MEG, ECOG and MRI studies (Pantev et al., 1990; Nakasato et al., 1994; Buchner et al., 1995). The replicability of the source location, amplitude, and latency is similar in EEG and MEG recordings (Virtanen et al., 1998).

Studies using dipole source analysis in infants and children are rare. An exception is the study of Vaughan and Kurtzberg (1992), who observed two additional temporal generators in 6-month-old infants besides the sources known in adults.

Several studies on the development of scalp LAEP have been published. Already 26 weeks postconception cortical

responses to auditory stimuli were observed in preterm infants (Vaughan and Kurtzberg, 1989). In the course of the first month of life remarkable changes take place. The latencies of LAEP shorten and the amplitudes increase. According to Vaughan and Kurtzberg (1992), the amplitudes reach their maximum at the age of about 5 to 6 months. It is assumed that amplitudes and latencies gradually decrease during further development. Several authors have reported that the amplitude of LAEP components in adults are smaller, latencies shorter, and variance less than in children (Callaway and Halliday, 1973; Goodin et al., 1978; Fuchigami et al., 1993; Tonnquist-Uhlén et al., 1995; Sharma et al., 1997). At the age of 14–16 years the LAEP were described to be nearly equivalent to the adult's LAEP (Steinschneider et al., 1992).

Ponton et al. (2000) recorded the LAEP from 30 scalp electrodes in subjects with ages between 5 and 20 years. The largest age-dependent changes were seen for the first components. The amplitude changes depended on the location of the scalp electrode. The authors suppose distinct maturational time courses for different LAEP generators. Oades et al. (1997) also reported age-dependent changes of the topography of several components. They studied the development of LAEP from the age of 10–21 years.

Despite these findings, our knowledge of changes in LAEP during development is still incomplete. Distinct developmental changes in the activity of the different intracortical generators of LAEP are assumed, but they have not yet been investigated. In the present study, we analyzed the scalp LAEP and their dipole sources in healthy children, adolescents, and adults in order to document the course of normal maturation of the activity of the auditory cortex.

2. Methods and materials

2.1. Subjects

We examined 87 normally developed children and adolescents (41 boys, 46 girls) and 21 healthy young adults (15 men, 6 women; ages 20–30 years). The children and adolescents attended a mainstream kindergarten or school, respectively. They were subdivided into 6 age groups: 5–6 years ($n = 11$), 7–8 years ($n = 20$), 9–10 years ($n = 16$), 11–12 years ($n = 13$), 13–14 years ($n = 14$), 15–16 years ($n = 13$). Participants with a history of neurological or psychiatric diseases, language or learning disorders, or dyslexia were excluded from the study. According to pure tone audiometry, all subjects had normal hearing threshold.

2.2. LAEP recording

The pure tone LAEP were recorded according to a standard oddball paradigm. A pseudorandomized order of stimuli was presented to the right ear via insert earphones. Tones at 1000 Hz with a duration of 175 and 15 ms rise and fall time were used as standard stimuli (933 sweeps). Rare

stimuli were frequency deviants (200 sweeps, 1200 Hz, 175 ms) and duration deviants (200 sweeps, 1000 Hz, 100 ms). The intensity was 86 dB SPL and the stimulus onset asynchrony (SOA) was constant at 1.0 s. Each session consisted of 4 sequences of 5.5 min each. The participants were instructed to ignore the stimuli. They watched a silent video tape during the recording session.

For source analysis 21 electrodes were placed according to the international 10/20 system (Jasper, 1958) and additionally at Oz and at the right and left mastoids. All electrodes were referenced to the right mastoid lead. The impedance was kept below 5 k Ω . The electro-oculogram (EOG) was recorded using electrodes positioned at the outer canthus of each eye and infra- and supraorbital to the left eye. Data were acquired using the Neuroscan system at a sampling rate of 256 Hz. The signals were bandpass-filtered on-line at 0.16–30 Hz and stored for off-line analysis.

2.3. Analysis of LAEP data

Standard stimuli epochs from 200 ms prestimulus to 800 ms poststimulus onset were averaged. Automatic artefact rejection excluded all trials with EEG-voltage exceeding ± 80 μ V (mean artefact rate: 6% of presented standard stimuli in children, 2% in adults). Amplitudes were measured against prestimulus baseline and latencies against stimulus onset.

Dipole source analysis was performed by BESA (Brain Electrical Source Imaging; Scherg, 1990) to calculate spatial-temporal models for the structures involved in the generation of the observed surface potential distributions. Components originating from different cortical generators but overlapping at the surface and disturbing each other, can thus be decomposed into single activities to be investigated separately. In prestudies we used a more realistic head model for the dipole source analysis. In comparison to the standard BESA model, the differences in localization of electrodes and localization and direction of dipole sources were insignificant. So we decided to apply the simpler standard BESA in a 4-shell spherical head model.

To obtain the dipole models, an iterative fit procedure is applied to optimize location parameters. From a given configuration of dipoles, the resulting surface potential distribution is calculated and compared to the observed distribution. A numeric algorithm is used to iteratively modify the spatial parameters in order to minimize the difference (measured by calculating the residual variance) between the observation and the model. In our study, we added another criterion for the ‘goodness of fit’, the energy criterion provided by BESA (weighted by a factor of 0.5). Not only the residual variance is taken into account, but also the energy of the source activity is minimized. Sources are assumed to be forced out of the deeper regions of the brain, an assumption that is based on the cortical origin of the LAEP. They are also hindered from building high-level

activities in closely spaced but oppositely oriented dipoles, which cancel each other at the surface and have no physiological counterpart.

An additional 20 Hz low-pass filter and transformation to average reference were applied to the surface data before analysis. Although signal quality was sufficient for estimating the LAEP parameters at the surface electrodes, the remaining noise and limited number of electrodes did not permit calculation of individual dipole source locations in many cases. To overcome this problem, the spatial source parameters were derived from the grand mean data of each age group. The temporal course of activity could then be calculated for the individual potential distributions, using the appropriate spatial model.

Calculations were started with regional sources, constrained to interhemispheric symmetry, as Scherg proposed (Scherg et al., 1989; Berg and Scherg, 1994). During the progress of fitting, constraining conditions were tested for justifiability.

Peak latencies and amplitudes were determined at the tangential (t) and radial (r) dipole sources. The parameters of components were estimated by automatic determination of the maximum of the positive and negative deflexion (time window of parameter estimation of tangential dipole source: P1t 0–160 ms, N1t 80–350 ms, P2t 120–200 ms and radial dipole source: P1r 30–160 ms, N1r 120–250 ms, P2r 160–330 ms after stimulus onset). Visual inspection afterwards ensured that the peaks were in the right time course and free of artefact distortion.

Analysis of variance (ANOVA) and correlation analysis were used for the statistical analysis of the data.

3. Results

The scalp LAEP in children differed considerably from that in adults (Fig. 1). The main developmental changes consisted of an increase in complexity of the LAEP waveform and the emergence of new components. In children we

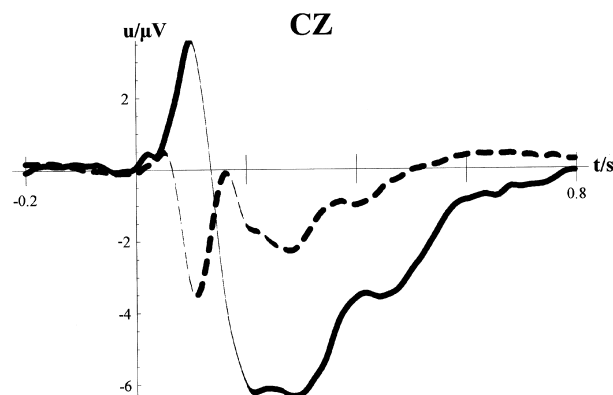


Fig. 1. Grand mean of LAEP at Cz (reference: linked mastoid electrodes) in pre-school children and adults. — pre-school children (5–6 years, $n = 11$); adults (20–30 years, $n = 21$).

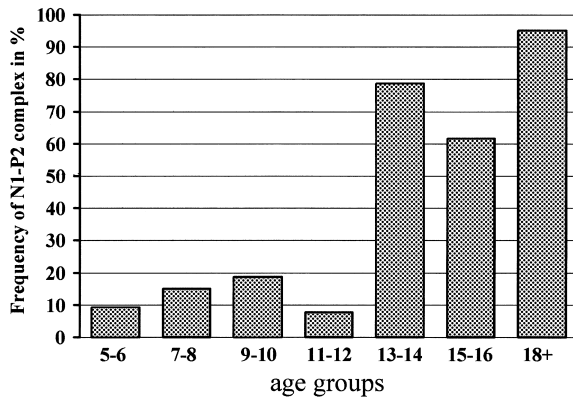


Fig. 2. Frequency of the N1-P2 complex at Cz as a function of age.

only seldom registered an N1-P2 complex, which is characteristic of adult's LAEP. Typical children's LAEP at Cz were composed of only two components, an early positivity at about 100 ms after stimulus onset and a later negativity with a latency of about 250 ms. The adult's LAEP were more complex. The most reliable components in adults were N1 and P2. Other components (P1, N2) were also elicited in many cases. The frequency of the N1-P2 complex significantly increased at the beginning of adolescence (Fig. 2). A comparison of the child's and adult's potentials revealed that the polarity of the first wave was opposite. The N2 of the adult's LAEP was similar to the negativity in children as regards latency. The amplitudes of all components were lower in adults than in children.

BESA was applied to calculate the generators of the LAEP. The dipole sources were estimated in a time window of LAEP activity according to the grand mean of the groups. Since the LAEP duration was shorter in adults than in children, the time window differed between the groups. More than 98% of the variance of scalp-recorded LAEP could be explained by two dipoles per hemisphere located in the temporal lobe in all groups. The number of dipole sources was equal in children and adults and localization and orientation were also similar (Fig. 3). One of the dipole pairs (dipoles 1 and 2) had a tangential orientation and was located in the superior temporal lobe. On the basis of its location and orientation, this tangential dipole can be assumed to represent the activity of the supra-temporal plane in the depth of the Sylvian fissure. The other dipole pair (dipoles 3 and 4), situated in the lateral temporal area, had a radial orientation. This dipole probably reflects the activity of the secondary auditory areas.

The activity of the tangential and the radial dipole sources differed greatly, especially in adults (Fig. 4). In adults the potential of the tangential dipole was composed of several components, whereas the activity of the radial dipole mainly consisted of a single negativity. In contrast, the complexity of the activity of the tangential and radial dipole sources was similar in childhood. In all groups strength and duration of the activity of the radial dipoles were less. The activities and

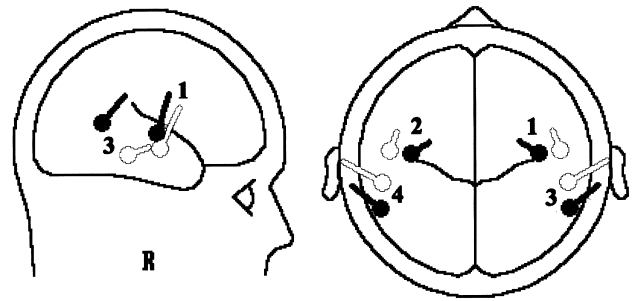


Fig. 3. Dipole sources of LAEP in pre-school children and adults. ○ pre-school children (5–6 years, $n = 11$), residual variance: 1.4% (68–571 ms); ● adults (20–30 years, $n = 21$), residual variance: 1.5% (91–319 ms).

the configurations of the right and left generators were similar.

Age-specific changes of the dipole activity were characterized by progressive shortening of peak latencies and a decrease of peak amplitudes (Tables 1 and 2). The variance of most parameters was greater in children than in adults. Analysis of variance (ANOVA) revealed significant effects of age on the latency and amplitude of the dipole source peaks. A significance level of $P < 0.001$ was found for the scores of all peaks. The correlations between age and peak parameters of the radial dipole were lower than those between age and tangential dipole parameters, but also highly significant ($P < 0.001$). The age-specific changes did not cease in childhood; considerable differences were also observed between the group of adolescents and adults.

In addition there was a change in component structure (Fig. 5). During adolescence a new component, the N1/P2 complex, appeared in the activity of the tangential dipole. In contrast, only rarely was an N1/P2 complex observed in childhood. The activity of the radial dipole was characterized by two positive and one negative peak in childhood. The amplitude of positive peaks was very low in adults. Often the activity of the adult's radial dipole source consisted of only one negative peak.

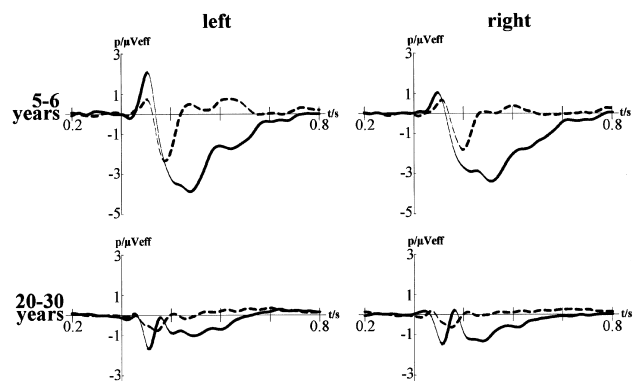


Fig. 4. Activity of dipole sources of LAEP in pre-school children and adults. — tangential dipole; radial dipole.

Table 1
Left hemisphere^a

Age (years)	Tangential (t) dipole source (primary auditory cortex)				Radial (r) dipole source (secondary auditory cortex)					
	P1t		N1t		P1r		N1r		P2r	
	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude
5–6	106 (9)	2.3 (0.9)	241 (47)	−4.6 (2.3)	91 (23)	0.9 (1.0)	172 (21)	−2.6 (1.5)	275 (28)	0.8 (1.3)
7–8	105 (10)	2.8 (1.5)	216 (47)	−5.3 (2.1)	97 (34)	0.9 (0.6)	170 (12)	−2.5 (1.1)	265 (26)	2.2 (1.7)
9–10	99 (13)	2.6 (1.1)	211 (36)	−4.4 (1.8)	89 (29)	0.7 (0.6)	172 (12)	−1.9 (1.0)	284 (35)	1.7 (1.0)
11–12	84 (18)	0.9 (0.8)	180 (22)	−4.7 (1.8)	84 (33)	0.8 (0.8)	159 (8)	−2.4 (1.4)	235 (23)	2.3 (1.2)
13–14	74 (27)	0.29 (0.7)	148 (43)	−2.2 (1.3)	82 (28)	0.5 (0.7)	150 (9)	−1.7 (0.7)	234 (31)	1.5 (1.1)
15–16	67 (16)	0.3 (0.5)	177 (53)	−2.3 (0.9)	85 (29)	0.7 (0.5)	154 (12)	−1.1 (0.7)	254 (38)	1.6 (0.7)
20–30	56 (16)	0.22 (0.3)	101 (10)	−1.8 (0.9)	61 (18)	0.2 (0.2)	149 (28)	−0.8 (0.4)	227 (37)	0.3 (0.3)
r_{sp}	−0.762	−0.723	−0.704	0.640	−0.331	−0.316	−0.593	0.560	−0.433	−0.301

^a Latency (ms) and amplitude (μ V eff) of dipole sources of LAEP at different age – mean (standard deviation); below Spearman correlation (r_{sp}) between age and LAEP parameters – significance level of all correlations $P < 0.001$.

4. Discussion

Studies on infancy have shown that important steps in LAEP maturation take place during the first months of life. However, age-dependent changes are not finished within the first year. We observed that LAEP develop throughout childhood and adolescence. In the course of childhood, there was not only a change in latency and amplitude but also one of component structure.

Dipole source analysis makes it possible to study the

developmental changes in the underlying activity of localized cortical regions. Thus, the process of maturation can be described in more detail. But till now dipole source analysis with BESA has only been applied in adults. It is unclear if BESA can be used without adaptation in children. Head size, thickness of the skull and denseness of the scalp differ between children and adults. However, these variables do not influence localization and direction of the calculated dipole sources. Only the amplitude of source activity could be higher with lower head size and thinner skulls. In view of

Table 2
Right hemisphere^a

Age (years)	Tangential (t) dipole source (primary auditory cortex)				Radial (r) dipole source (secondary auditory cortex)					
	P1t		N1t		P1r		N1r		P2r	
	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude	Latency	Amplitude
5–6	92 (25)	1.3 (0.8)	254 (56)	−3.9 (1.5)	102 (25)	0.8 (0.9)	199 (16)	−2.0 (1.6)	282 (23)	0.5 (1.0)
7–8	94 (11)	1.4 (0.7)	229 (54)	−4.8 (1.8)	122 (17)	1.2 (0.8)	183 (15)	−2.0 (1.0)	267 (25)	2.1 (1.1)
9–10	88 (12)	1.8 (0.9)	223 (29)	−4.0 (1.3)	113 (24)	0.9 (0.6)	181 (14)	−1.6 (1.0)	289 (35)	1.6 (0.8)
11–12	80 (26)	0.8 (0.7)	202 (49)	−4.5 (1.1)	107 (28)	1.0 (0.9)	166 (7)	−1.6 (0.6)	257 (25)	2.4 (1.2)
13–14	71 (12)	0.5 (0.6)	144 (53)	−2.3 (1.3)	98 (19)	0.6 (0.7)	157 (9)	−1.5 (1.0)	244 (30)	1.3 (0.9)
15–16	67 (21)	0.6 (0.6)	172 (52)	−2.1 (1.2)	112 (97)	1.1 (0.4)	166 (9)	−0.9 (0.8)	253 (34)	1.5 (0.7)
20–30	43 (19)	0.3 (0.2)	123 (35)	−1.6 (0.9)	70 (11)	0.2 (0.2)	154 (26)	−0.8 (0.4)	246 (45)	0.2 (0.3)
r_{sp}	−0.743	−0.634	−0.714	0.628	−0.507	−0.320	−0.722	0.407	−0.312	−0.317

^a Latency (ms) and amplitude (μ V eff) of dipole sources of LAEP at different age – mean (standard deviation); below Spearman correlation (r_{sp}) between age and LAEP parameters – significance level of all correlations $P < 0.001$.

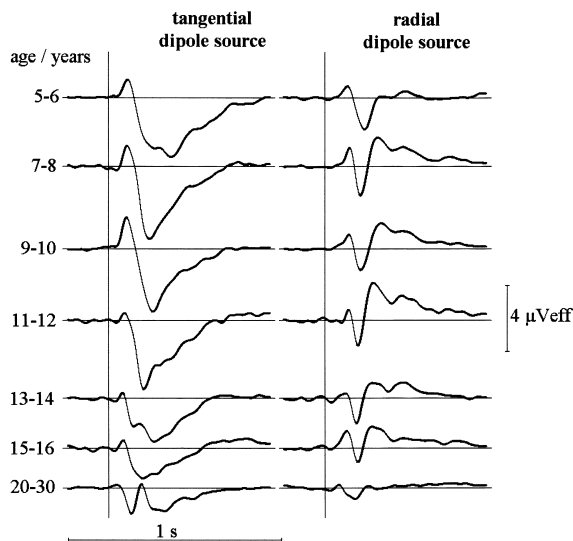


Fig. 5. Development of dipole source activity from childhood to adulthood (left hemisphere).

the simplification of BESA head model, we can assume that the standard BESA model is also usable in children.

In our study we were able to attribute the LAEP in adults to the activity of two bioelectrical sources per hemisphere in the temporal lobe. These findings correspond to results of several studies (Hegerl et al., 1994; Frodl et al., 1998). Scherg et al. (1989) described another temporal pair of dipole sources 14 mm anterior to the tangential dipole. They assumed that this dipole pair reflects the activity of the generator of the sustained potential. We could not reliably distinguish an additional dipole. Since the tangential and the additional dipole described by Scherg et al. nearly had the same orientation it was not possible clearly to decompose the tangential oriented activity into two distinct dipoles. Our results prove that the number of dipole sources of LAEP are the same in children and adults. The location and direction differ minimally, and the observed age differences in location and orientation are also insignificant. However, in view of the number of scalp electrodes we utilized, the resolution of dipole source analysis is too small to exclude minor differences between age groups.

Opinions differ on the development of scalp LAEP throughout childhood. There is general agreement that latencies are longer in children than in adults (Kraus et al., 1993; Fuchigami et al., 1993; Johnstone et al., 1996; Ponton et al., 2000). They are assumed to decrease most markedly during the first 3 years of life (Steinschneider et al., 1992). According to our findings latency changes continue until adolescence. After age 20 there is a gradual increase in latencies (Goodin et al., 1978; Pfefferbaum et al., 1980). In contrast, amplitudes remain a subject of controversy. They are believed to increase after birth. According to Vaughan and Kurtzberg (1992) the amplitudes reach their

maximum during the first year of life. Johnstone et al. (1996) studied the N1, N2, and P3 in an auditory oddball task in subjects 8–17 years old. They described a linear decrease of the N2 amplitude with age and an increase of the P2 amplitude to standard tones. They observed a decrease of the N1 amplitude only to target stimuli. In contrast, Fuchigami et al. (1993) found no correlation between age and N1 and N2 amplitude to target tones, whereas Johnstone et al. (1996) reported an increase of N1 and N2 amplitude to target and non-target stimuli. These differences might be due to the technique used to evaluate LAEP. Results depend on where the amplitude is measured. Ponton et al. (2000) stressed that the amplitude changes may have distinct courses depending on electrode sites.

Until now there has been no information on the development of the LAEP sources. The scalp LAEP reflects the activity of underlying cortical generators. We registered a gradual decrease of latencies of the peaks of dipole source activity, and the amplitudes diminished as well. The decrease of source activity parameters was not finished until the age of 16 years. In our study amplitudes were smaller and latencies shorter in adults than in adolescents. The variability of most source parameters was higher in children than in adults. Similarly Martin et al. (1988) reported a high variability of scalp LAEP at the age of 6–7 years, and Fuchigami et al. (1993) demonstrated a reduction in interindividual variations after the age of 9 years.

However, not only amplitude and latency of the scalp LAEP change throughout childhood. Our study showed that children have a different component structure than adults. The typical adult N1-P2 complex elicited by auditory stimuli was only seldom detected in children. The emergence of the N1/P2 complex in adolescence is related to a change of the tangential dipole source potential, which reflects the activity of the planum temporale and Heschl's gyrus. Already Courchesne (1990), who studied scalp-recorded LAEP, reported that infants and children have a positivity of about 85–120 ms instead of the adult N100 and a negativity of about 200–240 ms instead of the adult P200. He elicited the LAEP by speech stimuli. A similar component structure was elicited by tone stimuli (Csépe et al., 1992; Kurtzberg et al., 1995; Bruneau et al., 1997; Johnstone et al., 1996). Korpilahti and Lang, (1994) called the LAEP components in children P100 and N250. They did not find any significant difference in the P100/N250 complex between different stimulus paradigms. In agreement with our results Sharma et al. (1997) also observed the LAEP configuration characteristic for adults in only a few 6-year-old children and with age an increase of frequency of typical adult LAEP. The LAEP were elicited by synthesized speech stimuli. Authors suggested that the differences between children are caused by a different velocity of myelogenesis and synaptogenesis.

It is unclear which component of LAEP in adulthood corresponds to those in childhood (Sharma et al., 1997).

Kurtzberg et al. (1995) believe that N1, the first negativity of adult LAEP, is equivalent to N250 in children. Korpilahti and Lang (1994) explain the component structure in childhood and adulthood in a similar way. They suppose that N250 and N1 are identical potentials. N1 is superimposed over P2 in children because of N1's longer latency and less habituation. P2 would not be seen clearly until the N1 latency became shorter during adolescence. However, the adult P1 is also superimposed in adults for the same reason, due to the decreasing N1 latency. In contrast, Csépe (1995) argues that the two negativities are not identical, because the adult N1 wave depends on stimulus frequency and intensity but N250 in children does not.

Johnstone et al. (1996) hypothesize that the N250 is identical to the N2 wave, which is elicited in adults by target stimuli. They suppose that after standard stimuli the negativity becomes smaller with age, because the capacity to control the direction of attention increases. Finally, N2 or N250 only appears in adults after target stimuli.

Several studies have shown that the component structure of LAEP in children depends on the interstimulus interval (ISI). N250 disintegrates into different components with longer ISIs (Neville et al., 1993; Paetau et al., 1995; Korpilahti, 1996). Ceponienė et al. (1998) studied the relationship between ISI and LAEP systematically in children 7–9 years old. They discovered 3 negative waves instead of one N250, if the ISI was 2 s or longer. They suggest that the first negativity at about 160 ms after stimulus onset corresponds to the component 1 of the adult N1, since distribution and dependence of latency on ISI are similar. The latency of the second negative wave does not change with ISI and seems to be equivalent to the adult N2. The significance of the third negative wave at about 460 ms is unclear.

In our study only one negativity was detected in most children. In general we were able to distinguish among N1, P2, and N2 only at the beginning of adolescence. According to the findings of Ceponienė et al. (1998), we can assume that because of a relatively short SOA (1 s) in our study, N1 and N2 form only one single activity. Oades et al. (1997) used a longer ISI (1.2–1.7 s) and registered a clear N1-P2 complex at least in adolescents. However, we did not find different dipole sources of N250, which would represent an overlapping N1 and N2. Both N1 and N2 were found to be generated in a narrow area of the auditory cortex. Their generation sites might be too close to be differentiated by the applied method of source analysis. Limited by the number of electrodes and signal quality, only one pair of dipoles represents nearby, yet possibly distinct activities in our model.

The activity of the radial dipole source is characterized by a negativity at about 150–170 ms after stimulus onset. According to Ceponienė et al. (1998), this potential represents the component 2 of N1. Adults generally exhibit only a single potential, a rather low negativity. In contrast, a distinct positivity before and after the negativity was seen

in school-age children. The positivity in the activity of the radial source in children does not seem to be identical with the familiar P2 component of the vertex LAEP in adults. Due to the radial dipole direction, the activity radiates to temporal leads and is not visible at Cz or Fz.

Age-dependent LAEP changes reflect a maturational process. The shortening of ERP latencies is usually considered a sign of increased transmission velocity due to increase of axonal diameter, myelination, and perceptual processing speed (Tonquist-Uhlén, 1996), whereas changes in amplitude are assumed to indicate changes in the magnitude of the involved synaptic activity during perceptual processing (Vaughan and Kurtzberg, 1992). The change of LAEP waveform probably also reflects reorganization in perceptual processing such as greater synchronization of neuronal activity, the establishment of more effective network structures, and the increasing automation of information processing.

LAEP changes throughout childhood are complex. The dipole source analysis seems to be a useful tool for studying developmental processes of localized auditory functions. Further studies in children with central auditory impairment, developmental language disorders, or dyslexia are recommended.

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