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The Relation between Electric Auditory Brain Stem and Cognitive Responses and Speech Perception in Cochlear Implant Users

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Electrically evoked brainstem responses (EABR) and event-related cortical potentials were recorded in seven postlingually deaf adults who were experienced users of a Nucleus multichannel cochlear implant. The patients were divided into two subgroups: good performers and moderate performers. Poor EABR were found in two of the moderate performers. The latencies and amplitudes of the cortical N1–P2 complex in the good performers were within the same range as those of subjects with normal hearing, but were deviant in the group of moderate performers. This may indicate disturbed cochleotopical organization of the auditory cortex in the latter group. P300 measurements in the good performers showed normal latencies, whereas in the moderate performers they were prolonged. The results suggest that the outcomes of electrophysiological measurements to assess the integrity of a patient's auditory neural system on a brainstem and a cortical level, are related to the patient's performance with the cochlear implant. *Key words*: *ABR, ALR, auditory evoked potentials, cochlear implantation, P300, speech perception.*

INTRODUCTION

One of the challenges in cochlear implant (CI) research is to explain the variability in the results of patients with a CI. In general, the performance of patients with a CI range from simple sound detection to the perception of open speech. It has been argued that the loss of integrity of the auditory neural system may play a significant role. One of the variables on a peripheral level, is eighth nerve survival. The number of surviving spiral ganglion cells in profoundly deaf patients varies widely, even in patients with a similar cause and duration of deafness (1, 2). Large variation in neural cell degeneration has also been found on a central auditory pathway level (3).

In several animal studies, the number of surviving spiral ganglion cells has been related to the outcomes of electrically evoked brainstem response (EABR) measurements. The rationale was whether or not nerve survival in man can be assessed with (non-invasive) EABR measurements. In animals, several authors found a relation between EABR measurements and spiral ganglion cell survival, while others did not (4, 5). There is conflicting evidence regarding the value of EABR measurements to assess eighth nerve survival. However, EABR measurements remain indispensable, as they reflect the integrity of the entire auditory brainstem region.

EABR studies on man have shown a waveform morphology which is comparable with that found during acoustic stimulation, but with shorter latencies (4, 6–10). In most studies, EABR were determined to assess their value as an estimator of subjective thresholds in CI patients (7, 10). Very few studies have related EABR measurements with patients' performance with a CI. Abbas and Brown (9) reported poor, non-significant correlations between EABR measurements and speech recognition scores in CI patients.

Apart from eighth nerve survival and brainstem integrity, processing in the auditory cortex may play a role in the unexplained variability in CI benefit. Cortical processing of sounds by CI users has been studied using electrophysiological measurements. The morphology and latencies of the endogenous cortical peaks N1 and P2 in CI patients were found to be within the same range as those in subjects with normal hearing (6, 11, 12). Ponton et al. (13) showed that the N1–P2 complex yielded information about the site of cortical activation. Using spatio-temporal source modelling, sources for the N1–P2 complex were found to be "distributed in an orderly pattern along the superior surface of the temporal lobe". They reported that two patients who were using a multichannel CI, had similar source activity as subjects with normal hearing during acoustic stimulation. The source activity of a CI patient with non-auditory sensations was quite different (13).

Task-related P300 measurements using tone bursts in patients with a CI were performed by Kaga et al. (14) and Oviatt and Kileny (11). It was argued that the P300 latency might be related to the phonemic and linguistic discrimination abilities of CI patients (11). In CI patients who had problems discriminating

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Table I. *Some patient characteristics*

No.	Age at onset (years)	Duration of deafness* (years)	Etiology	Composite score† (%)
1	27	11	unknown	90
2	7	20	meningitis	88
3	37	7	mumps	85
4	7	39	meningitis	76
5	37	26	unknown	75
6	44	15	otosclerosis	74
7	36	21	meningitis	67

* Duration of deafness is the difference in years between the onset of deafness and cochlear implantation.
† A composite score for speech perception was obtained, which was the average score for a monosyllable test, a spondee test, a long-vowel recognition test, and a short-vowel recognition test (see Material under Material and Methods).

between the two test tones in a psychophysical experiment, they found significantly prolonged P300 peaks. The more problems the patient had discriminating between the two test sounds, the more the P300 latency was prolonged. Compared to subjects with normal hearing, P300 latencies in CI patients were reported to be prolonged from 70 msec for very distinct stimuli (0.5 and 3 kHz tone bursts) to 130 msec for less distinct stimuli (0.5 and 1 kHz tone bursts) (11).

P300 measurements using speech in successful CI patients were performed by Micco et al. (15). They found no significant differences in N1 and P2 latency and P300 amplitude and latency between the group of CI patients and a group of age-matched subjects with normal hearing. The N1 amplitude was significantly smaller in the CI patients. They did not compare the electrophysiologic results to behavioural results of speech perception.

In the present study, the EABR threshold was determined from the EABR measurements. Prior to EABR testing, the subjective threshold of the EABR clicks was also determined. It was hypothesized that the bigger the difference between the subjective threshold and EABR threshold, the poorer the quality (synchronization) of neural activity, with obvious consequences for speech recognition. In addition, EABR input–output functions were determined. The working range of the auditory neural system and the slope of the input–output function are known to be related to speech recognition abilities. It has been assumed that poor growth of output with increasing input, indicates that very few neurons are active, which suggests global transmission of the information to the auditory cortex.

As suggested by Oviatt and Kileny (11), P300 measurements may reflect the patient's auditory discrimination abilities. We did P300 measurements using tone burst and compared P300 latency and amplitude to speech perception data.

EABR and cortical evoked responses were measured in experienced postlingually deaf CI patients and related to their well–documented long-term speech perception abilities. A distinction was made (based on speech perception results) between a group of good performers and a group of moderate performers.

MATERIAL AND METHODS

Subjects

Seven adult postlingually deaf patients with a Nucleus multichannel CI with a mini speech processor (MSP) participated in the experiments. Audiological measurements prior to implantation showed total deafness in all cases which meant: the hearing thresholds at 0.5 kHz exceeded 110 dB hearing level (HL) and at 1, 2, 4 and 8 kHz they exceeded 120 dB HL. Some patient data are presented in Table I. In all the patients, the electrode array was inserted into the cochlea over its full length. The patients were experienced and successful users of the CI; they had been using it all day for more than 3 years.

For comparison, event-related potentials evoked with acoustic stimulation were also measured in a control group of 11 subjects with normal hearing (hearing thresholds at 0.25–8 kHz were 20 dB HL or less) with no known neurological or otological diseases or complaints. The age of the control subjects varied from 22 to 57 years, with a mean of 33 years.

Material

The measurement of EABR has been described in detail in a previous paper (10). Biphasic pulses ("clicks") of 400 μsec/phase were used at a repetition rate of 12.5 pulses per second. Relatively broad clicks and a broad bipolar +3 stimulation mode were chosen in order to minimize the number of instances that no EABR would be obtained due to insufficient stimulation. Recording electrodes were placed on the

mastoid contralateral to the stimulation (reference) and on the forehead (Fz, active). The earth electrode was connected to the wrist. The band-pass filter settings of the registration system (Medelec ER94) were 0.1 and 3000 Hz. For each measurement condition, 1024 averages were applied. To minimize the effect of stimulation artifacts, recordings were obtained on the side contralateral to the stimulation.

Prior to EABR testing, the subjective threshold, Most Comfortable Level (MCL) and Uncomfortable Loudness Level (ULL) of the EABR clicks were determined in a psychophysical experiment. The EABR clicks were presented at an identical stimulation rate as that used in the EABR measurements. This was done for the same three pairs of electrodes that were used for EABR testing, namely the basal pair 1–5, the medial pair 9–13 and the apical pair 18–22. ULL determinations were not obscured by maximum output levels of the CI in any of the subjects.

The first measurement was obtained at the MCL. The level of the clicks was decreased in steps of about 10% of the subjective dynamic range to determine the EABR threshold. Subsequently, measurements were performed with the stimulation levels increasing stepwise up to the ULL. In this way, input–output (I/O) functions were obtained; Fig. 1 shows a typical example. "Input" concerns the stimulation level (in current level steps or CLS), while "output" concerns the amplitude of wave V. From the I/O functions, three measurements were derived: *i)* the difference between the EABR threshold and the subjective threshold (TD; threshold difference in CLS); *ii)* the dynamic range (DR, also expressed in CLS), i.e. the range in which growth of output was found with increasing input; and *iii)* the slope of the I/O function. To calculate the slope according to Abbas and Brown (9), the input was expressed in mA and the slope in μV/mA.

If the output was saturated, the DR was determined by fitting two lines through the I/O data points, as indicated in Fig. 1 for electrode pair 18–22. The intersection of the two lines was considered to represent the upper limit of the DR, with the EABR threshold as the lower limit. When no saturation occurred, the DR was the difference between the ULL and EABR threshold. In the case of saturation, the slope of the I/O function was the slope of the steepest part, prior to saturation.

P300 measurements were carried out with tone bursts, using an oddball paradigm. A 0.5 kHz tone burst (20 msec linear rise and fall time, 80 msec plateau time) was used as the frequent stimulus, while a 1 kHz tone burst (with the same envelope) was used as a rare stimulus. The stimuli were presented by a loudspeaker placed 1 m in front of the patient. The frequent stimuli occurred at a probability rate of 85% (about 200 times); the rare stimuli occurred at a probability rate of 15% (30 times per measurement). The presentation level at the position of the patients' ears was approximatelly 70 dB(A) (measured with Bruel and Kjaer 2203 soundlevel meter). The interstimulus interval was 2 sec. Prior to testing, the patient was asked to adjust his/her speech processor to a comfortable listening level.

The patients were instructed to count the rare stimuli. The number counted was verified after the measurement. Six out of the seven patients found it easy to discriminate between the two tone bursts. One patient had some problems.

The recording of two frequent stimuli following a rare stimulus was not included in the average. Recording electrodes were placed on the contralateral mastoid (reference), on the parietal midline (Pz, active) and on the wrist (ground). The band-pass filter settings of the registration system (Medelec ER94) were 1 and 125 Hz. The measurements were low–pass filtered digitally off-line, with a cut-off frequency of 25 Hz. Measurements contaminated by eye movements were detected and excluded from the average. The measurement was repeated once and the results were averaged. The latency and amplitude of peaks N1, P2 and P300 were determined by eye.

At 2 years postimplant, several speech perception tests are administered to CI patients as part of the evaluation procedure in the Nijmegen CI programme. The procedure and the tests were described by Hinderink et al. (17). Speech recognition at this evaluation moment is used as reference. A composite score is obtained, which is the average score for a monosyllable test (4AFC), a spondee test (4AFC), a long-vowel recognition test (5AFC) and a short-vowel recognition test (4AFC). Averaging occurs after correction for different chance levels (17). The composite scores (CS) in our group of patients varied from 67 to 90%, see Table I. Based on these scores, the patients were divided into two subgroups: one group comprised the good performers (CS between 85 and 90%, patients 1 to 3) and the other group comprised the moderate performers (CS between 67 and 76%, patients 4 to 7).

RESULTS

EABR measurements

Reproducible EABR were measured in six of the patients (see Table II). Typically, two to three peaks were found, the most dominant peak (resembling acoustic peak V) was found between 3.6 and 4.0 msec. In patient 5, a reproducible response could only be detected at the apical pair of electrodes. In the

Table II. *Individual EABR results of the CI patients subdivided into group A (good performers) and group B (moderate performers) according to their speech recognition scores*

Sub-group	No.	Present	TD (CLS*)	DR (CLS)	I/O slope (μV/mA)
A	1	+†	25	50	2.9
	2	+	10	65	1.3
	3	+	40	50	5.0
B	4	+	35	90	1.7
	5	±			
	6	−			
	7	+	25	50	3.5

* CLS, current level steps.
† +, present, −, absent.

other five patients, responses were detected at all three pairs of electrodes. In the remaining patient (patient 6), no reproducible EABR could be recorded, not even at stimulation levels close to his ULL. From the EABR I/O functions, the TD, DR and the slope were calculated. Saturation of the output was found in two of the patients; a typical example is given in Fig. 1. A one-way analysis of variance ANOVA did not show any significant differences in the TD, DR or the I/O slope between the three stimulation sites within the patients with reproducible EABR recordings. Therefore, these parameters were pooled per patient; the mean TD, DR and slope values per patient are presented in Table II. All three good performers had reproducible EABR. Only

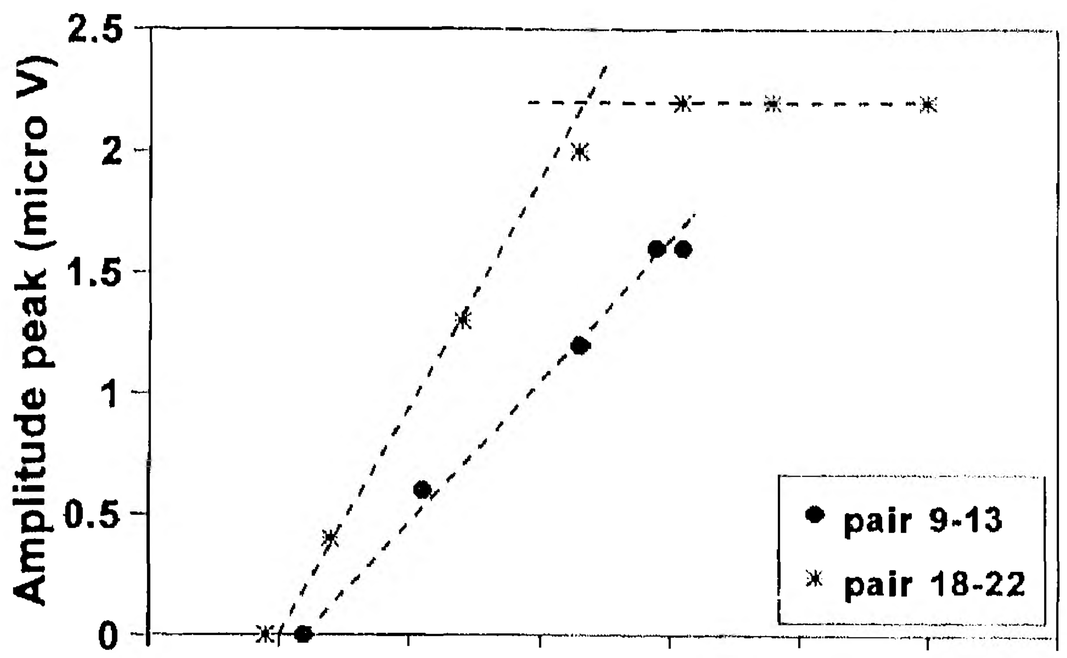

Fig. 1. Characteristic input–output function of one of the patients. The input is the stimulation current (CLS or current level steps), output is the amplitude of peak V. The result of electrode pair 18–22 shows saturation. The subjective thresholds for the EABR clicks for electrode pairs 18–22 and 9–13 were 70 CLS and 72 CLS, respectively.

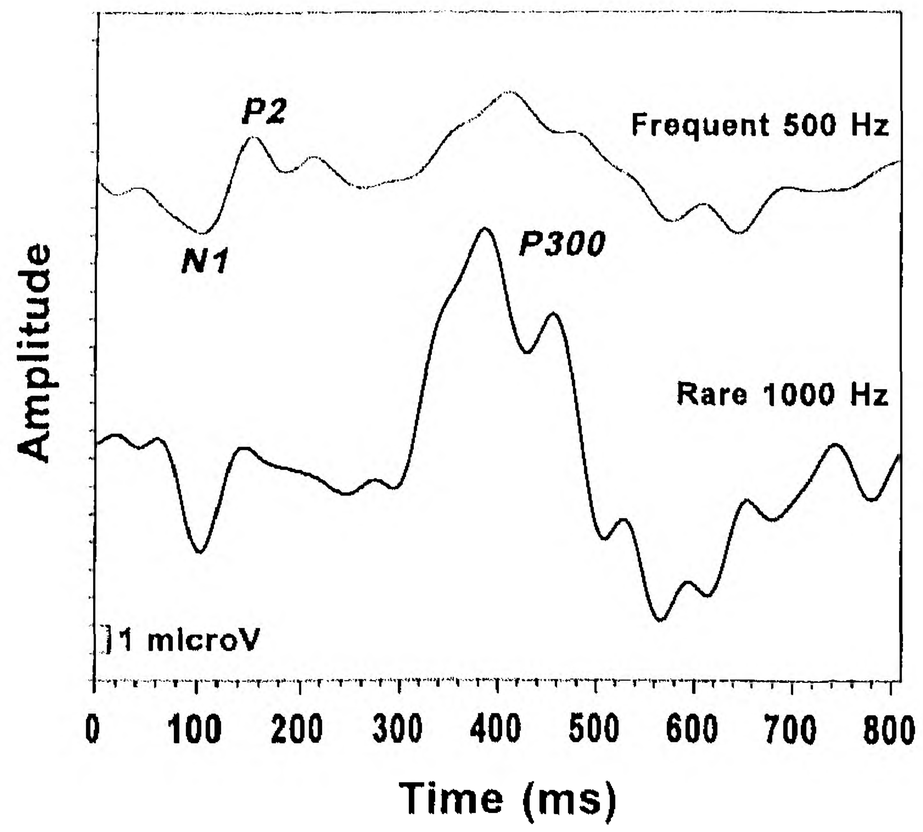

Fig. 2. Typical example of a P300 measurement in one of the CI users. The cortical peaks N1, P2 and P300 are indicated.

three out of the four moderate performers had good EABR. The TD, DR and slope values were within the same range in the two patient groups. All the slope values were well within the range of those reported by Abbas and Brown (9).

P300 measurements

A reproducible P300 peak was found in six out of the seven patients. The P300 of the remaining patient was absent. This patient (patient 4) was the only one who had problems identifying the rare stimuli correctly, so an additional P300 measurement was carried out with 0.5 kHz tone bursts as the frequent stimuli and 3.0 kHz tone bursts as the rare stimuli. This time, the patient had no problems identifying the rare stimuli and a clear P300 was produced.

A typical example of a P300 measurement obtained from one of the CI users is presented in Fig. 2. The cortical peaks N1, P2 and P300 are indicated. The latencies and amplitudes of the P300 peak in the standard measurement condition are presented in Fig. 3. The latencies and amplitudes of the N1 and P2 peaks taken from the average trace of the 0.5 kHz frequent tone burst are also presented in this Fig. As a reference, the results of control subjects with normal hearing are presented as well (median values and range).

The N1 latency, N1 amplitude and P2 amplitude of the CI patients as a group, did not differ significantly from those of the control subjects. However, the CI patients did demonstrate significantly prolonged P2 latencies ($t(16) = 2.66$, $p < 0.05$).

The CI patients were divided into two subgroups according to their speech perception scores. In Fig. 3, the results of the good performers are indicated by dots,

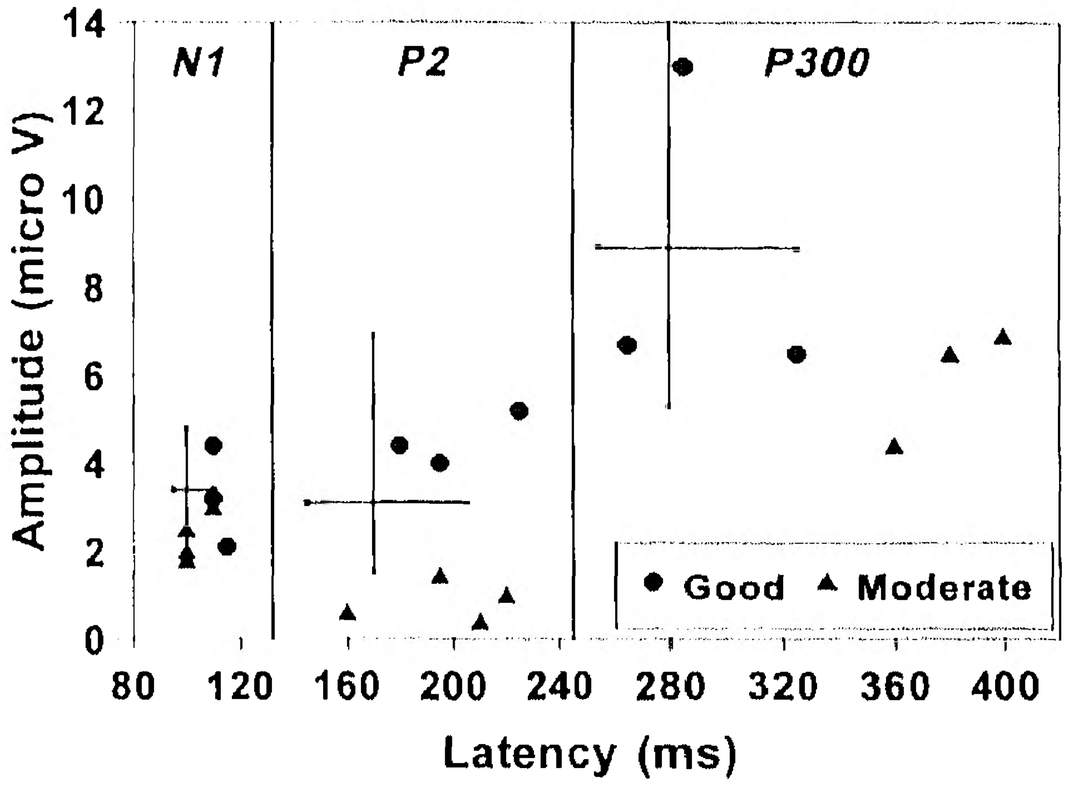

Fig. 3. Latencies and amplitudes derived from the P300 measurements. The N1 and P2 values were obtained from the average trace of the frequent stimuli (0.5 kHz tone bursts). The results are indicated by circles for the good performers and by triangles for the moderate performers. For reference purposes, the results of a control group (subjects with normal hearing stimulated acoustically) are also shown; the median values and the ranges of the amplitudes and latencies of the three peaks are indicated by lines.

while those of the moderate performers are indicated by triangles. There were minor differences in peak N1 between both subgroups, whereas larger amplitudes were found for peak P2 in the good performers. The P300 latencies of the three good performers were on average 90 msec shorter than those of the moderate performers. Most of the amplitudes and latencies of peaks N1, P2 and P300 of the good performers were within the normal range (except for the N1 latency in one patient and the P2 in another patient). In all of the moderate performers, the amplitude of the P2 peak and the P300 latencies were outside the normal range.

The N1–P2 complex is endogenous, just like the brainstem response. It should be mentioned that the two patients who had either no reproducible EABR or a reproducible EABR for only one electrode pair, had the two poorest amplitude values in the N1/P2 complex.

DISCUSSION

In one of the patients, no reproducible EABR was found, while in a second patient, reproducible EABR were only found at one electrode pair. This implies that the auditory potentials were absent or unrecognizable. As these two patients could definitely perceive sound, it means that either too few neurons were activated or the synchrony of the firing neurons was poor. When EABR were present, the level of the threshold was always well above the subjective threshold of the EABR clicks (positive TD values, see Table II). In subjects with normal hearing, the objective EABR threshold and the subjective thresholds, generally coincide during acoustic stimulation (16). The experimental condition may have played a role. Poor signal-to-noise conditions do not seem to be a major factor, because extrapolation of the supra-threshold data (with good signal-to-noise ratios) as shown in Fig. 1, indicated that the EABR threshold occurred at values exceeding the subjective threshold. The width of the relatively broad pulse applied in this study may have been responsible. Systematic discrepancies between the EABR threshold and the subjective threshold using the same stimuli (clicks) have been reported by Van den Honert and Stypulkowski (4) and by Allum et al. (8), who obtained their results with shorter pulse widths (50 and 200 μsec/phase, respectively). Therefore, it can be concluded that at relatively low but effective stimulus levels, distinct compound action potentials were not recognizable. This may reflect poor synchrony of the firing nerve fibres. Comparable findings have also been observed in patients with normal hearing who have spiral ganglion neuropathies (18).

The DR values of the patients were fairly homogeneous; no discernable differences were seen between the two subgroups (Table II). Measurement of the dynamic range has often been debated because its determination is highly dependent upon the patient's concept of ULL. It was not possible to detect a relation between the slope of the EABR I/O function and the composite speech recognition score in the present study. This is in accordance with the findings of Abbas and Brown (9).

The amplitudes and latencies of the N1–P2 complex measured in the total CI group were in accordance with the values in subjects with normal hearing, except for the small but significant difference in P2 latency. This result confirms the findings by Pelizzone et al. (6), Oviatt and Kileny (11) and Brix and Gedlicka (12).

In order to evaluate the overall effect, a distinction was made between good and moderate performers. The amplitude of the endogenous cortical N1–P2 complex of the moderate performers, was poorer than that of the good performers. This suggests that the cochleotopical organization of the auditory cortex is less distinct in moderate performers, as can be deduced from the N1–P2 complex (13).

The moderate performers obtained poorer results in the electrophysiological experiments on a brainstem level and/or on a cortical level. It is not clear from the present study whether the results on a brainstem and a cortical level are directly related, but the presence of EABR and the amplitude of the N1–P2 complex suggest a possible relation.

The P300 measurements showed that the characteristics of the good performers were within the same range

as those of subjects with normal hearing when stimulated acoustically, while the latencies of the P300 peak were significantly prolonged in the moderate performers. The latter indicates that these patients had more problems discriminating between the two tones than the others, although they did count the number of rare stimuli correctly. Generally, as it becomes more difficult to discriminate between two sounds, the P300 peak becomes more prolonged (16). When we compared our results to those of Oviatt and Kileny (11) who used the same set-up as the present one, we found that our latencies were shorter in the subjects with normal hearing and in the CI patients. At present we have no explanation for this difference. Furthermore, they found that the P300 latency of all the CI patients was longer than normal, by an average of approximately 60 msec. In the present study, similar observations were only made in the group of moderate performers.

CONCLUSIONS

Although the number of patients was small, some conclusions can be drawn. Distinct differences were found in the electrophysiological measurements between the patients on a brainstem and a cortical level. The best CI performers had good EABR and more pronounced endogenous cortical peaks than the moderate performers. The latter fact suggests that they have better cochleotopical organization of the auditory cortex. P300 latencies were shorter in the best performers, which is consistent with better auditory discrimination abilities in the best performers, than in the moderate performers. Furthermore, the parameters derived from the cortical measurements in the best performers were all within the range of or close to the values obtained from subjects with normal hearing during acoustic stimulation.

On the basis of the present results, we recommend further investigation into the role of neural integrity assessments using electrophysiological measurements in patients with a CI, in order to study the variability in benefit among CI users.

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