BRAINSTEM RESPONSE AUDIOMETRY IN THE DETERMINATION OF LOW-FREQUENCY HEARING LOSS

E.A.J.G. CONIJN

Brainstem Response Audiometry in the Determination of Low-Frequency Hearing Loss

A study of various methods for frequency-specific ABR-threshold assessment

Hersenstamaudiometrie bij de bepaling van de laagfrekwente gehoordrempel

Een onderzoek naar verschillende methoden voor bepaling van de frekwentie specifieke hersenstam response drempel

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CONTENTS

CHAPTER I

GENERAL INTRODUCTION

Spontaneous bioelectric activity generated from the central nervous system (EEG) was first described by Berger in 1929. The principles of Auditory Brainstem Response (ABR) recording date back to 1938, when Loomis et al. reported the change in the on-going EEG caused by sensory stimulation.

However, the voltage of the spontaneous EEG far exceeds the change in the EEG brought about by sensory stimulation. Therefore, various attempts were made to extract the EEG changes related to sensory stimulation (Dawson, 1951, 1954; Geissler et al., 1958). The process of averaging, described by Clark et al. (1961), has been the most successful.

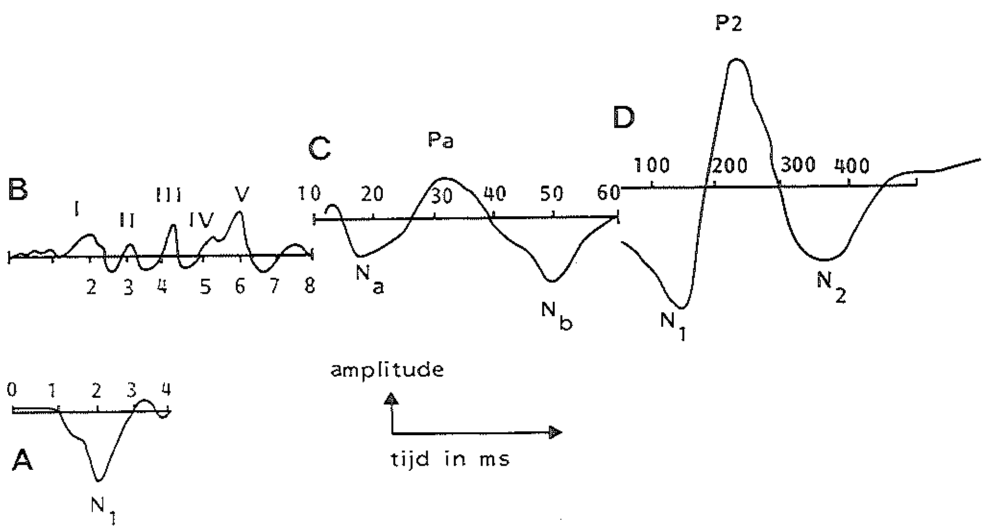

Figure 1
Examples of auditory evoked responses, classified by the time of appearance after stimulus onset: A. Cochlear potentials with a latency of 0-5 ms (electrocochleography); B. Early latency or Auditory Brainstem Responses (ABR) with a latency of 0-15 ms; C. Middle latency responses generated by the mid-brain and the cortex, with a latency of 10-100 ms; D. Long latency responses generated by the cortex, with a latency of 100-1000 ms

The averaging technique increases the signal to noise ratio. In this way the measurement of the responses to sensory stimuli has become possible. One of the sensory responses which could be identified is the response to sound.
These Auditory evoked potentials are classified by the time at which they appear, measured from stimulus onset (Figure 1).
The first class of responses, the cochlear potentials (A), differ with regard to the other classes in that they require an electrode placement near the cochlea and thus are "near" field potentials. The far field potentials (B, C, D) are volume conducted, and can therefore be recorded relatively far away from the neural generator site. The electrode placement is less critical than with "near field" potentials.

The Auditory Brainstem Response (ABR), with latency ranging from 0 to 15 ms was first described by Sohmer and Feinmesser in 1967. But it was Jewett in 1970, who definitively identified and classified the auditory brainstem response peaks. The classification by Jewett, who named the first 5 vertex positive peaks I through V, respectively, is now uniformly used.

The ABR is usually elicited by repeatedly presenting an auditory stimulus to a subject (Figure 2) through a headphone. The electric response is detected with the help of skin-electrodes, usually attached to the vertex and retroauricular area (mastoid). After amplification, filtering, artefact rejection, and averaging, the response is plotted against time after stimulus onset on an X-Y-plotter. Although different sounds can be used, the most widely used stimulus is a click; a short acoustic stimulus with a duration of 50-100 μs.

With this click stimulus a robust and reliable ABR can be obtained (Figure 3). A hearing threshold can be determined by attenuating the stimulus until no response peak can be seen (Figure 3).

The ABR has found wide clinical acceptance because of its reliability, low inter- and intra subject variability, and above all, because it can also be recorded in sleeping or anaesthetized patients.

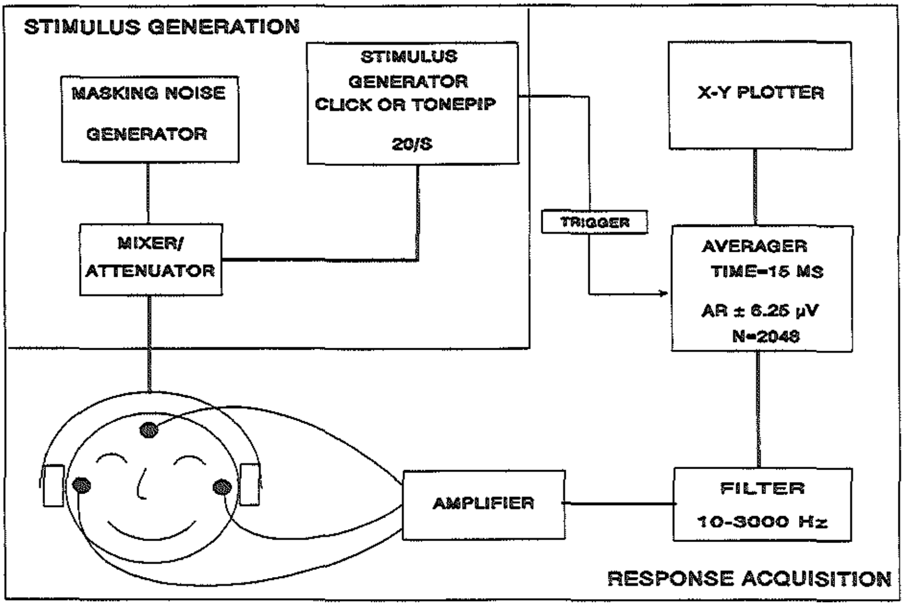

Figure 2
Schematic drawing of the equipment used in this thesis. For details see the following chapters.

Two major applications for the ABR have evolved:

1. The first application originates from the field of neurology, in which the ear is used to stimulate the brain with a "shock", usually a loud click sound. Over the years the ABR has evolved as a specific and sensitive instrument to detect lesions in the brainstem e.g. due to acoustic neuroma's. Lesions in the brainstem can be detected by the longer inter-peak time interval.
2. The second application originates from the field of Ear Nose and Throat surgery. The brain and brainstem are regarded as a "window" on the ear. With the help of the ABR, objective determination of the sensitivity of the ear to sound is possible: an objective hearing threshold, further referred to as ABR-threshold (Figure 3). This objective method is especially useful for determining the hearing threshold in uncooperative patients (e.g. children).

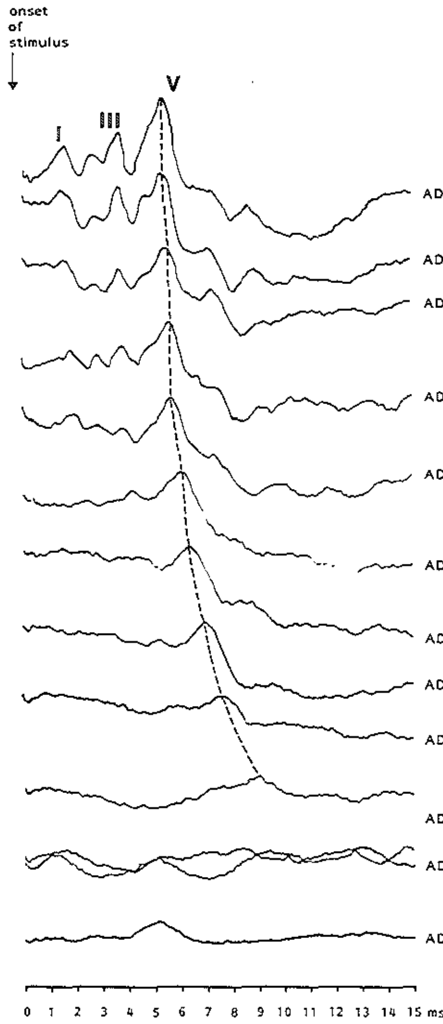

Figure 3

Example of a series of Auditory Brainstem Responses of the right ear (AD) of a normal hearing subject. The stimulus level is given in dB nHL. At the stimulus level of 90 dB nHL the response peaks are classified according to Jewett. The ABR-threshold, defined as the lowest stimulus level at which peak V can be seen in the response, is 10 dB nHL. At the stimulus level of 5 dB nHL the ABR is reproduced to exclude any response. The dashed line points to the Jewett Peaks V.

This thesis focuses on the second application, the objective determination of a hearing threshold. As recent work in our clinic by van der Drift (1988) again demonstrated, the ABR-threshold can be regarded as a reliable indicator of the loss of sensitivity to sound. This ABR-threshold is, as is usually the case, elicited by a click stimulus. This click stimulus has a "white" frequency spectrum, which means that all frequencies are present with an equal amount of energy. Because of the tonotopical organization of the basilar membrane (each frequency component of the stimulus excites a specific place on the basilar membrane), it can be expected that the entire basilar membrane is stimulated by a click stimulus. Therefore, the response to clicks is a result of the sensitivity of the basilar membrane to sounds of all frequencies.
However, the studies of van der Drift (1988) demonstrated again that the ABR-threshold is dominated by the sensitivity of the 3000 Hz area of the basilar membrane. Therefore, the ABR-threshold to a click stimulus can be regarded as high-frequency-specific (frequency-specificity is defined as the quality of the ABR-threshold to correspond with the pure-tone threshold in a specific, limited, pure-tone frequency band, and not with those outside this frequency band, or with much less weight).
As hearing loss usually starts, and is most severe, in the higher frequencies, the use of the ABR-threshold to clicks may lead to an overestimation of the hearing loss in the lower (500, 1000 Hz) frequencies, which are important for speech recognition. Furthermore, an exclusively low frequency (500, 1000 Hz) hearing loss, which seriously jeopardizes speech development (Alberti et al., 1983), might go undetected. So, for the diagnosis, as well as for hearing aid fitting, reliable information about the low frequency sensitivity of the ear is desirable. If a low-frequency ABR-threshold can be assessed, the construction of a two point ABR-audiogram can become possible, with the routine click-evoked ABR-threshold serving as high-frequency point.

There are good indications that a low-frequency threshold can be obtained using electrocochleography (For a review see Eggermont 1976) or middle latency responses (Thornton et al., 1977; McFarland et al., 1977). The first method is, however, an invasive method, which needs electrode placement through the eardrum near the cochlea, and, therefore, requires general anaesthesia in children. The success of the second method depends on the arousal state of the subject, which is not easily controlled in uncooperative subjects.

Because the Auditory Brainstem Response is a method which can be used in sleeping and anaesthetized subjects, and is non-invasive, much research has been directed in using the ABR for low-frequency-specific threshold assessment. Although various methods have been proposed, none has gained wide clinical acceptance. (The reasons for this are discussed in this thesis.)

Two major strategies for obtaining a low-frequency specific ABR-threshold can be discerned:

1. The use of masking noise.
2. The use of brief tonal stimulation (tonebursts, tonepips or filtered clicks).

1. The use of masking noise is based on the assumptions that:
   a. concomitant presented noise can inhibit an ABR.
   b. this effect can be restricted to a certain frequency domain by presenting noise with a restrained frequency domain.
   c. the minimal necessary masking noise level is linear with the stimulus level.

If these assumptions are true, than the masking noise can inhibit a response from some parts of the basilar membrane without interfering with the response from other parts of the basilar membrane, and thus creates a frequency specific response. The basic assumptions, together with the research and the clinical implications of this masking noise method, are discussed in chapters III and V.

2. The use of brief tonal stimulation is based on the assumption that this kind of stimulation is frequency-specific in itself. The electrical and acoustical spectrum of these kind of stimuli can be made reasonably narrow (see page 30, Figure 1), and also psychophysical experiments (Davis et al., 1984) show that these stimuli are frequency-specific. This, however, does not imply that the ABR elicited by brief tonal stimuli is frequency-specific. This is due to the fact that apparently only the first part of the stimulus is used by the cochlea for eliciting the ABR (Kodera et al., 1983). Because of the trade off between time and place (Gabor, 1947), the frequency spectrum broadens when a shorter part of the stimulus is used. This fact, together with the asymmetry of basilar membrane excitation, and with the better overall sensitivity in the 2000 to 4000 Hz area (Borg, 1981), causes that low-frequency brief tonal stimuli easily elicit ABRs mainly originating from a higher frequency region on the basilar membrane, than targeted for (Kinarti and

Sohmer, 1982; Beattie and Boyd, 1985; Laukli and Mair, 1986). Therefore, many authors believe it to be impossible to obtain a low-frequency-specific ABR with the use of brief tonal stimulation.

Although much research has been done into this field, both into the masking method and into the brief tonal stimulus method, most of these studies are done with normal hearing subjects or with small groups of hearing impaired subjects. The lack of well documented studies on patients with hearing loss is striking. It is very important that a method is studied in subjects with hearing loss, not only because it is this group of subjects for whom the method is eventually intended, but because subjects with hearing loss can have a diminished frequency selectivity. Frequency selectivity is the ability of the cochlea to differentially analyze sounds with different frequencies. Loss of frequency selectivity can diminish the effectiveness of masking noise (Gorga, 1983), and can render the tonal stimulus less frequency specific (Chapter IV).

This study was designed to study both the masking method and the brief tonal stimulus method for obtaining low-frequency auditory brainstem responses. Some parts in this study were done with normal hearing subjects, to obtain normative values (Chapter III and IV). Other parts were done with hearing impaired subjects (Chapter V and VI). In chapter VII, the unmasked click evoked ABR-threshold is compared with the high-pass-noise-masked ABR-threshold, as to their specificity for the optimum correlated pure-tone frequencies (1000 an 3000 Hz, respectively). This was done to examine whether the unmasked click evoked ABR-threshold is sufficient high-frequency-specific to serve as a high-frequency point in a two point ABR-audiogram.
General conclusions are discussed in Chapter VIII.

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CHAPTER II

CHOICE OF CENTRE FREQUENCY

Low-frequency usually means 500 and 1000 Hz in this field of research. Apart from the question whether it would add much extra information, the testing of both frequencies is very time consuming. ABR-threshold testing can take up to 60 minutes per frequency and per stimulus type for both ears, depending on how much reproducing is necessary, and depending on the percentage of the responses which are rejected by the artefact rejection, due to patient restlessness. As the patients also were examined by routine click-evoked ABR testing, we had to restrict ourselves to one low frequency.

As 1000 Hz is only an octave away from the 2000 to 4000 Hz region, which is elicited by the normally used click stimulus, it would be better if the 500 Hz frequency could be used.

In a pilot study to the detectability of the ABR-thresholds to 500 and 1000 Hz filtered clicks and to high-pass masked clicks with a "centre frequency" of 500 and 1000 Hz (cut-off frequency 890 and 1590 Hz respectively), the ABR-threshold was some 15 dB higher for 500 than for 1000 Hz regardless of the method. In 2 out of 5 normal hearing subjects, who were examined with the 500 Hz stimulus, no response at all could be seen.

This is in agreement with the literature. Gorga et al. (1988), who used digitally generated tonepips, found reliable responses to 750 and 1000 Hz tonepips but not to 500 Hz tonepips. Hawes and Greenberg (1981), who used 1/3 octave filtered tonepips, reported that responses for 500 Hz, if present, were not as well defined as those for 1000 and 2000 Hz.

Don et al. (1979), using a high-pass masked click and the derived response technique, reported an ABR-threshold of 30 dB nHL with cut-off frequencies of the high-pass masker between 500 and 1000 Hz, and an ABR-threshold of 10 dB nHL with cut-off frequencies of 1000 and 2000 Hz.

The results of the 500 Hz studies are, thus, more variable, the amplitude of the responses lower, and the ABR-threshold for normally hearing subjects higher than for 1000 Hz. This higher threshold seriously decreases the dynamic range in which stimulation is possible. We, therefore, think that the choice of the 1000 Hz frequency gives the better chance to realize the aim of this study: an objective, simple, reliable and non-invasive method which can be used in sleeping or anaesthetized subjects to obtain a low frequency hearing threshold.

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CHAPTER III

MONAURAL VERSUS BINAURAL AUDITORY BRAINSTEM RESPONSE THRESHOLD TO CLICKS MASKED BY HIGH-PASS-NOISE IN NORMAL HEARING SUBJECTS

ABSTRACT

Monaural and binaural Auditory Brainstem Response (ABR) thresholds to clicks masked by high-pass noise with a cut-off frequency of 1590 Hz were measured in normal hearing subjects. In sleeping normal hearing subjects the 1000 Hz frequency-specific ABR-threshold for binaural stimulation amounted to 12 dB nHL and for monaural stimulation to 18 dB nHL. No significant difference in latency was found between monaural and binaural stimulation. Binaural ABR-threshold was 5.5 dB ± 1.4 dB (mean ± SEM) lower than the mean monaural ABR-threshold. This difference is statistically significant (Student's t test; $p<0.005$).

RESUMÉ

Des potentiels évoqués auditifs du tronc cerebral spécifiques en fréquences basses ont été enregistrés avec stimulation monaurale ou binaurale par un clic masqué par un bruit aux fréquences au-dessus de 1590 Hz. Chez les sujets normaux et endormis le seuil monaural est 18 dB nHL et de 12 dB nHL avec stimulation binaurale. Les latences des pics sont égales pour stimulation monaurale et binaurale. Chez les sujets normaux le seuil monaural est en moyenne 5,5 dB au-dessus du seuil binaural. Cette différence moyenne est significative avec un ecart-type de 1,4 dB.

INTRODUCTION

Van Zanten and Brocaar (1984) reported that frequency-specific auditory brainstem responses (ABR) to binaurally presented clicks masked by notched noise can be obtained in normal-hearing subjects. If the same method is to be used to obtain a low-frequency-specific ABR-threshold in patients with a cochlear hearing loss, it is of course necessary to use monaural stimulation instead of the binaural stimulation used by Van Zanten and Brocaar.

In various reports (van Olphen et al., 1978; Prasher et al., 1981; Wrege and Starr, 1981; Gerull and Mrowinski, 1984) monaurally and binaurally stimulated ABRs have been compared, but these comparisons were all done at a stimulus level well above ABR-threshold. A binaural-monaural response amplitude ratio between 1.6 and 1.9 is reported. This ratio, however, increases when the stimulus level decreases (Wrege and Starr, 1981; Fowler and Leonards, 1985). Extrapolating this, the binaural-monaural response amplitude ratio is expected to be 2 near the ABR-threshold. As

the ABR-threshold is defined as the lowest stimulus level at which the amplitude of the response can be detected, the ABR-threshold for binaural stimulation can be expected to be lower than for monaural stimulation. In the literature, however, no data could be found about this effect.
The present study was done to determine the magnitude of the difference between monaural and binaural stimulated ABR-thresholds and to establish normative data for future research; ABR-thresholds both for binaural and for monaural stimulation are reported to enable a direct comparison between monaural and binaural data. The click stimulus was masked with high-pass noise to enable direct comparison with the earlier-mentioned study of Van Zanten and Brocaar (1984) and to establish normative data of low-frequency-specific ABR.

METHODS

Subjects

Ten normal hearing subjects were tested: 6 males and 4 females. Their pure-tone threshold was measured and at or below 15 dB nHL for 0.5, 1.0, 2.0, 4.0 kHz. All subjects were between 20 and 35 years of age. They were instructed to lie down on a bed in an acoustically insulated chamber and to relax. Six subjects slept during the session.
The stimulus was presented monaurally and binaurally to each subject via a TDH 39 headphone with MX-41/AR ear-cushions.
Monaural stimulation was randomly administered to a left or a right ear.

Stimulation and Masking

A click stimulus was generated with alternating polarity and an electrical duration of 100 μs at a repetition rate of 20 Hz. The levels for the click are expressed in dB nHL which means relative to the mean behavioral threshold in normal-hearing subjects. By calibration via an artificial ear (B&K 4153) 0 dB nHL was found to be equivalent to 34 dB peSPL. For reference reasons the levels for the click are expressed relative to the unmasked click. The behavioral threshold of the click masked by high-pass noise, as described below, was 14 dB above the behavioral threshold of the unmasked click. The masker was generated by a white noise generator (General Radio 1382). This noise was passed through a filter (Kemo VBF/24, 135 dB/octave) used either as a high-pass filter or as an all-pass filter. The latter mode resulted in a white-noise masker, 0 dB nHL was equivalent to 24 dB SPL. With this white-noise masker the

appropriate masking level was determined as the lowest masking level at which no response in the ABR to a 60 dB nHL click was found. The masker sensation level was at least 15 dB above the click sensation level (S/N ratio 5 [dB peSPL-dB SPL]). The masker level was then locked to the click level and the filter was switched to the high-pass mode with a cut-off frequency of 1590 Hz (two-third octave above 1000 Hz).
The high-pass masked click was attenuated (Hewlett Packard 350 D) in 10 dB steps well above the ABR-threshold and in 5 dB steps near the ABR-threshold.

ABR Recording

ABRs were recorded with silver chlorided cup electrodes. A two channel recording was made, the positive inputs were connected to the subject's vertex and the negative inputs to both mastoids. A forehead electrode was used for the zero-lead. The inter-electrode impedances were kept below 3 kΩ.
The response was amplified 10^4 times and band-pass filtered from 10 to 4000 Hz. The filter slopes were 24 dB/octave (Krohn-Hite 3322).
The response was averaged over 2048 sweeps that did not exceed ± 6.25 μV (artifact rejection). A time base of 15 ms was used.

ABR Identification

As our ABRs resemble those described by Suzuki et al (1981) we also use his nomenclature and call the first positive peak P10 and the following negative trough N15 (Figure 1).
At stimulus levels near the ABR-threshold the responses were repeatedly measured to test replicability. The responses were judged by the first and second authors. The lowest stimulus level at which P10/N15 could be replicated was scored as ABR-threshold (Figure 1).
The latency measurements were determined for the positive peak (P10) just prior to the negative trough (N15) (Figure 1).

RESULTS

Of the 10 subjects examined, 6 were asleep and their responses were of an excellent quality with a good signal to noise ratio (Figure 1). As the signal-to-noise ratio is low near ABR-threshold we considered these responses separately.

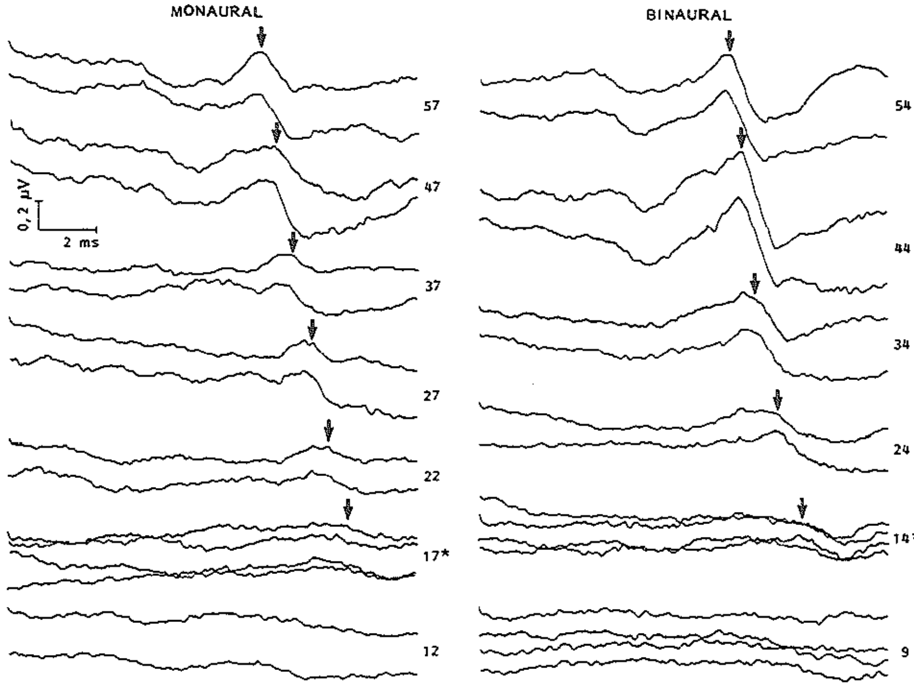

Figure 1

An example of low-frequency-specific ABRs of a sleeping subject. In the left panel with monaural stimulation, right with binaural stimulation. Stimulation level is given in dB nHL with each response pair. For monaural stimulation the upper trace in each pair is the ipsi-lateral recording, the lower one, the contralateral recording. ABR-threshold level is indicated with an asterisk. P10 is indicated with an arrow.

Four left ears and 6 right ears were stimulated monaurally.

For the monaurally stimulated ear, the mean pure tone threshold at 500 Hz was 4.0 dB, at 1000 Hz 2.0 dB, and at 2000 Hz 2.5 dB. For the other ear the mean pure tone threshold was 3.5 dB, 2.5 dB and 2.0 dB at 500, 1000 and 2000 Hz respectively.

In Table I the results for the monaural and binaural ABR-thresholds are shown, together with the mean pure tone threshold for 1000 Hz both for the monaurally stimulated ear and for the other ear. Italic printed data refer to sleeping subjects.

The mean monaural ABR-threshold for all subjects is 22.0 dB nHL with a SEM (standard error of the mean) of 1.8 dB. For the sleeping subjects the mean monaural ABR-threshold is 17.8 dB nHL.

Table I
For each subject the pure-tone threshold at 1000 Hz for the monaurally stimulated (PTT MONAURAL) and the other ear (PTT OTHER) are given together with the ABR-threshold for binaural and for monaural stimulation. The data for the sleeping subjects are printed in italic.

SUBJECT NO.	PTT MONAURAL	PTT OTHER	ABR THRESHOLD BINAURAL	ABR THRESHOLD MONAURAL
10	10	15	19	32
11	*0*	*5*	*14*	*22*
12	*0*	*-5*	*14*	*17*
13	15	10	29	27
14	*5*	*10*	*14*	*17*
15	*5*	*5*	*14*	*17*
16	*-5*	*-10*	*9*	*17*
17	-5	0	19	27
18	*-5*	*-5*	*9*	*17*
19	0	0	24	27
MEAN	2/*0*	2.5/*0*	16.5/*12.3*	22.0/*17.8*
Std. err.			2.0	1.8

For the binaural ABR-threshold these figures are 16.5 dB nHL with a SEM of 2.0 dB for all subjects and 12.3 dB nHL for the sleeping subjects.
In Figure 2 the histogram of the differences between monaural and binaural ABR-threshold is shown. It shows a normal distribution ranging from -2 to 13 dB for all subjects but a narrower distribution for the sleeping subjects.

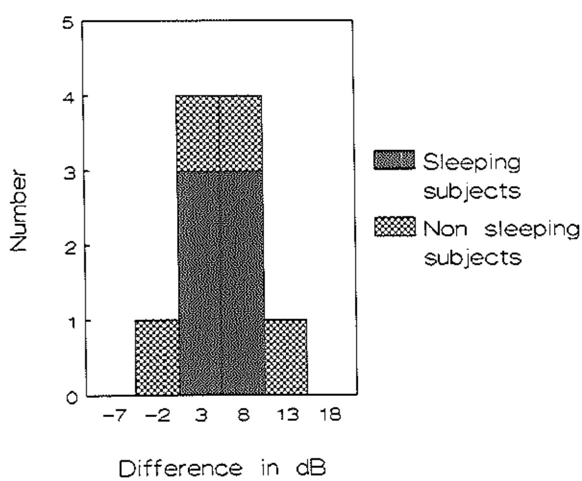

Figure 2
Histogram of the differences between binaural and monaural ABR-threshold.

The mean difference between the binaural and the mean monaural ABR-threshold is 5.5 dB. This difference is statistically significant (Student's t-test $p<0.005$). The SEM of the difference is 1.4 dB.
For the sleeping subjects alone the binaural-monaural threshold difference also amounts to 5.5 dB. The SEM is probably lower than 1.4 dB, but the distribution of the differences deviates too much from normal to allow calculation of the SEM (Figure 2).

In figure 3 the mean latency and standard deviation of the latency of peak P10 for each stimulus level are shown both for monaural and binaural stimulation (only data

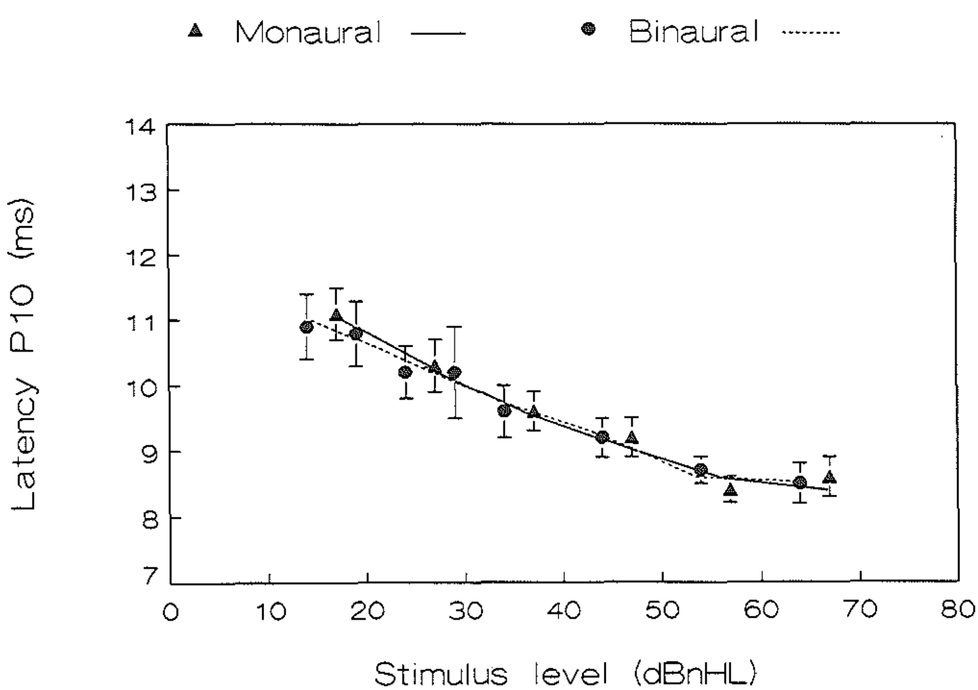

Figure 3
Mean latency of P10 plotted as function of stimulus level. Error bars indicate ± 1 SEM. The latency-level functions are fitted by eye.

points which comprise 3 or more latency measurements are shown). The resulting latency-level function is also shown in Figure 3. In contrast to the difference in ABR-threshold no significant difference could be found between monaural and binaural stimulation for the latency of P10 at any stimulus level.

DISCUSSION

In the present study the ABR-threshold for binaurally presented clicks masked by high-pass noise with a cut-off frequency of 1590 Hz was found to be 16.5 dB nHL. The binaural ABR-threshold for sleeping subjects alone amounted to 12.3 dB nHL. This is consistent with the report of Van Zanten and Brocaar (1984).
For monaurally presented clicks, the ABR-threshold was found to be 22.0 dB nHL for all subjects and 17.8 dB nHL for the sleeping subjects. This is in the same range as reported by other authors. Eggermont (1979) reported an ABR-threshold for derived responses of 1000 Hz of 15 dB nHL. Thümmler and Tietze (1984) used a click masked by high-pass noise. With a cut-off frequency of 1800 Hz the ABR-threshold was 10 dB nHL and with a cut-off frequency of 1250 Hz the ABR-threshold was 20 dB nHL.

The difference between ABR-thresholds of sleeping and awake subjects is very interesting. Although the number of subjects is small, the difference in ABR-threshold between sleeping and awake subjects suggests the importance of sleep when a low-frequency ABR-threshold is measured. Although recently, Deacon-Elliott et al. (1987) could not establish any influence of sleep on the click stimulated ABR-threshold, several other authors (Davis and Hirsch, 1979; Beattie et al., 1984) have reported about the importance of sleep for obtaining low-frequency specific ABR-thresholds. This could be due to the fact that the click stimulated ABR has a better signal to noise ratio than the low-frequency stimulated ABR. The low-frequency ABR has a poor signal to noise ratio at ABR-threshold level. Sleep results in a lower noise level and thus increases the signal to noise ratio. As the ABR-threshold is defined as the lowest stimulus level at which a response can be detected, a higher signal to noise ratio will result in a lower ABR-threshold (Elberling and Don, 1987). Nevertheless, the exact influence of sleep on the low-frequency specific ABR-thresholds has yet to be established.

As mentioned in the introduction, various authors (van Olphen et al., 1978; Prasher et al., 1981; Wrege and Starr, 1981; Gerull and Mrowinski, 1984) compare monaurally

and binaurally stimulated auditory brainstem responses. But only comparisons of ABR amplitudes are made at stimulus levels far above the ABR-threshold level and no direct comparison of the ABR-thresholds.
In the present study a direct comparison was made between binaural and monaural stimulated ABRs at threshold level.
The binaural-monaural ABR-threshold difference amounted to 5.5 dB with a SEM of 1.4 dB. Although in some individual cases the small left-right difference in the pure-tone sensitivity can be of some influence, no left-right differences were present in the mean pure-tone sensitivities (Table I). Therefore it is unlikely that the binaural-monaural ABR-threshold difference is confounded by left-right differences in ear sensitivity.
When starting this study we expected to find some result but not a figure that equals 6 dB within experimental error. Apparently, it is necessary to halve the sound pressure of the stimulus when changing from monaural to binaural stimulation and returning at threshold level. The literature (Wrege and Starr, 1981; Fowler and Leonards, 1985) suggests a binaural-monaural amplitude ratio of 2 at just above ABR-threshold levels. If we assume a linear relation between the sound pressure of the stimulus and the amplitude of the response at around threshold levels, as reported by Elberling and Don (1987) for click stimuli, then our binaural-monaural ABR-threshold difference of 6 dB can be explained.

A direct comparison of the amplitude between monaural and binaural ABR is very difficult at or near ABR-threshold level. By definition the signal to noise ratio is low at or near ABR-threshold levels and peak P10 has a rounded shape (Figure 1) with a comparatively large variability. Therefore only the difference of ABR-threshold level has been considered.

No significant difference in latency could be found between monaural and binaural stimulation which is consistent with the literature (Howe and Decker, 1984). As mentioned above, the binaural stimulated ABR can be regarded as a summation of the monaural responses. This summation will not alter the latency but only the amplitude of the response. Therefore no latency difference is expected.

Conclusions:

1. In normal hearing subjects, the low-frequency-specific ABR-threshold to binaural stimulation is significantly below that of the monaurally stimulated low-frequency-specific ABR-threshold.
2. The ABR-threshold difference between monaural and binaural stimulation amounts to 5.5 dB ± 1.4 dB.
3. No significant difference in latency is found between monaural and binaural stimulation.
4. In sleeping normal hearing subjects the 1000 Hz frequency-specific ABR-threshold amounts to 12 dB nHL for binaural stimulation and to 18 dB nHL for monaural stimulation in the present study.

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CHAPTER IV

FREQUENCY-SPECIFICITY OF THE AUDITORY BRAINSTEM RESPONSE ELICITED BY 1000 HZ FILTERED CLICKS

ABSTRACT

In normal-hearing subjects and in subjects with a flat cochlear hearing loss Auditory Brainstem Responses (ABRs) were recorded at various levels of a 1000 Hz filtered click stimulus with and without high-pass filtered masking noise. The difference in latency of the major peak in the ABR for the masked and unmasked condition was zero at the ABR-threshold. We regard this as proof of the frequency-specificity of the 1000 Hz filtered click stimulated ABR-threshold. The difference between ABR-threshold and the subjective pure-tone threshold at 1000 Hz amounted to 19 dB in normal-hearing subjects and to 10 dB in subjects with a flat cochlear hearing loss. This is probably related to loss of temporal integration and an abnormal loudness growth (recruitment).

RESUMÉ

Chez les sujets normaux et chez les patients présentant une surdité de perception avec une audiogramme plat, des potentiels évoqués auditifs du tronc cérébral spécifiques en fréquence ont été enregistrés à différentes niveaux d'intensité pour un clic filtrés centré sur 1000 Hz. Les clics filtrés ont été présentés dans le silence et sur un fond de bruit masquant les fréquences au dessous de 1590 Hz. L'écart de latence du pic principal dans les potentiels évoqués avec ou sans le bruit masquant est zéro au seuil objectif, mais il se montait au dessus de 2 ms pour les niveaux de stimulation surpassant 50 dB sur le seuil objectif. Ce fait démontre que les seuil objectif est spécific en fréquence de 1000 Hz. L'écart de seuil subjectif et objectif se trouvait 19 dB pour les sujets normaux et 10 dB pour les patients. Ce différence est peut être en relation avec le phénomène du recrutement.

INTRODUCTION

The auditory brainstem response (ABR) has been used for estimating the amount and type of hearing loss (van der Drift et al., 1987, 1988[a], 1988[b]; Conijn et al., 1989). Although a click stimulus activates the whole basilar membrane (Don and Eggermont, 1978), the click stimulated ABR-threshold corresponds with the higher frequencies (2000 and 4000 Hz) in the pure-tone audiogram (van der Drift et al., 1987; Coats and Martin, 1977; Jerger and Mauldin, 1978; Gorga et al., 1985)
This click-stimulated ABR-threshold can overestimate the hearing loss in the lower "speech" frequencies because in most cases cochlear hearing loss starts and is most severe in the higher frequencies. A hearing loss in low frequencies only may even go undetected by click-stimulated brainstem evoked response audiometry. For these reasons a low-frequency-specific ABR is desirable.

Two major approaches for obtaining low-frequency-specific ABRs can be distinguished.
The first one involves masking noise to isolate frequency-specific response area's in the cochlea. Some authors (Don et al., 1979; Picton et al., 1979; Thümmler and Tietze, 1984; van Zanten and Brocaar, 1984) have claimed good low-frequency-specific responses with masking techniques. Others (Pratt and Bleich, 1982; Pratt et al., 1984; Sohmer and Kinarti, 1984; Laukli, 1983; Laukli et al., 1988) have not found good low-frequency-specific responses.
Difficulties encountered in these techniques are the accurate relative levels of signal and masker and the possibility of spreading of the masking noise especially at high stimulus levels (Evans and Elberling, 1982; Gorga and Worthington, 1983).

This article focuses on the second major approach: the use of brief tonal stimulation, this term comprises both filtered clicks and tonebursts (short duration gated sinusoids).
The great advantage of this technique is its simplicity. On many ABR equipment this brief tonal stimulus is standard incorporated.
Davis and Hirsh (1976) were among the first to use brief tonal stimulation to evoke auditory brainstem responses. They reported that, near threshold level, the ABRs initiated in the apical turn are so difficult to identify with certainty that they are not likely to be of clinical value.
In contrast, Suzuki and Horiuchi (1977) obtained good results. A major difference with the experiments of Davis and Hirsh (1976) was that the high-pass cut-off frequency of the response filter was lowered to 0.3 Hz compared to the 100 Hz cut-off frequency of Davis. Stapells and Picton (1981) recommended a cut-off frequency of 10 or 20 Hz and Mason (1984) one of 20 Hz. With this low cut-off frequency, responses were obtained with the most reliable threshold indicator in the region of 10-20 ms after stimulus onset (Davis and Hirsh, 1979; Suzuki and Horiuchi, 1977; Suzuki et al., 1981[a]).
Another difficulty with brief tonal stimulation is the choice of an optimal rise-fall time of the stimulus. Most studies (Cobb et al., 1978; Kodera et al., 1977[a]; Stapells and Picton, 1981; Suzuki and Horiuchi, 1981[b]; Beattie et al., 1984; Davis et al., 1984) recommend the use of a rise-fall time between 2 and 5 ms. A longer rise-fall time will decrease the response amplitude because of lower neuronal synchronicity.

Even if an optimal stimulus rise-fall time and optimal response filter settings are chosen, the low-frequency-specific ABR is low in amplitude. Therefore optimal relaxation and preferably sleep is necessary to improve the S/N ratio for a reliable low-frequency threshold (Kodera et al., 1977[b]; Davis and Hirsh, 1979; Stein et al., 1981; Beattie et al., 1984; Conijn et al., 1990).

But even if all the above mentioned prerequisites are met, there is much discussion in the literature regarding the frequency-specificity of the low-frequency brief tonal stimulus.
In Table I a schematic survey is given of the hereafter mentioned literature.
Davis et al. (1985) reported "good results" for both 500 and 1000 Hz tonebursts. The subjects were several hundreds of children suspected of hearing loss. Good results are claimed, but no comparison with pure-tone audiometry was available. Kobayashi et al. (1985) reported a high degree of correspondence between ABR-threshold and behavioral threshold in hearing-impaired children. The stimulus was presented binaurally. The correlation between the behavioral- and ABR-threshold were 0.90, 0.95, 0.97 for 500, 1000 and 2000 Hz respectively. However the steepness of the pure-tone audiogram and the dynamic range of the pure-tone hearing loss are not specified. Hawes and Greenberg (1981) reported good results for 1000 Hz but not for 500 Hz. Hayes and Jerger (1982) reported a high correlation between the ABR-threshold to tonebursts of 500 and 2000 Hz and the pure-tone audiogram. However, in individual cases the ABR-threshold at 500 Hz overestimated the degree of hearing loss at that frequency. Kodera et al. (1977[b]) also reported a high correlation both in high and low-frequency hearing loss. Also for newborns, clinical useful responses were reported by Yamada et al. (1983) as well.

In contrast to the above mentioned authors there are others who doubt the frequency-specificity of a low-frequency brief tonal stimulus. These studies are shown in the lower half of Table I.
Kinarti and Sohmer (1982) reported on 80 subjects with normal-hearing and 11 with low-frequency hearing loss. One-third octave filtered clicks of 500 and 1000 Hz were used. It was not reported whether the subjects were asleep. In the patients with low-frequency hearing loss, the ABR-threshold was, on average, 47 dB better than the pure-tone audiometric threshold at the same frequency. The response of the filtered clicks had a similar wave form as the clicks. This was also the case when normal-hearing subjects were examined. In normal-hearing subjects, very small difference in

TABLE I

Schematic survey of some literature regarding brief tonal stimulated ABR. Respectively the following items can be seen: Author; Number of subjects; ***Response filter*** *passband (Hz);* ***STIMulus*** *rise-time and when present plateau time and fall-time (ms), in some cases 1/3 octave filtered click (1/3 OCT.) is used;* ***Sleep*** *during ABR recording (Yes or No);* ***Pure Tone Audiogram; AGReement:*** *whether Yes or No the authors regard their stimulus as feasible for frequency-specific threshold estimation;* ***Comment****, LFHL(low-frequency hearing loss).*

Author	No.	Resp. Filter	Pip	Sleep	PTA	AGR	Comment
Davis	>100	50-1700	2-1-2	Y	N	Y	
Kobayashi	42	8-400	2-2	Y	Y	Y	PTA not specified
Hayes	37	30-1000	2.5-2.5	N	Y	Y	No agreement in LFHL
Hawes	40	30-1000	1/3 oct.	N	Y	Y	Normal hearing subjects
Kodera	16	16-1000	5-5	Y	Y	Y	
Kinarti	91	200-5000	1/3 oct.	?	Y	N	
Beatti	10	55-1500	4-4	Y	Y	N	Suprathreshold
Kileny	18	150-3000	2-2	N	Y	N	Suprathreshold
Burkard	6	30-3000	2-1-2	N	Y	N	Suprathreshold
Laukli	10	30-3000	2-1-2	N	Y	N	Suprathreshold
Jacobson	5	30-3000	2-1-2	N	Y	N	Suprathreshold

latency was measured between filtered-click evoked and click evoked ABRs both with a stimulus level of 59 dB SL. However, when high-pass masking was used an appropriate latency difference was obtained. The authors concluded that the ABR evoked by low-frequency filtered-clicks is initiated in basal regions of the basilar membrane. Beattie and Boyd (1985); Kileny (1981); Burkard and Hecox (1983) and Jacobson (1983) also reported considerable latency delay when the toneburst stimulus is masked by high-pass noise. Laukli and Mair (1986) recorded both ABRs to clicks and 500 Hz tonebursts, using the derived band paradigm in 10 normal-hearing subjects. The stimulus level was 90 dB nHL. The derived-band analysis showed that both click and 500 Hz toneburst had a similar distribution of activity in the cochlea with the largest contribution coming from the 2000 to 4000 and 4000 to 8000 Hz bands.

Almost all of the above mentioned evidence against the frequency-specificity of the low-frequency brief tonal stimulus is based on stimulus levels far above ABR-threshold level. In contrast, the authors who reported good results, although many studies are open to criticism, have all done experiments at threshold levels. In the reports of Eggermont (1976); Klein and Teas (1978), Kramer and Teas (1979) and Folsom (1984), some evidence can be found that the frequency-specificity is perhaps better at ABR-threshold level.

We therefore hypothesized that low-frequency brief tonal stimulation is not frequency-specific far above ABR-threshold level but perhaps is at ABR-threshold level. If this hypothesis is accepted, then this will elucidate much of the controversy on low-frequency brief tonal stimulation.
To test this hypothesis, the frequency-specificity of 1000 Hz filtered clicks was investigated by comparing ABR latency with and without high-pass noise masking as a function of stimulus level both in normal-hearing subjects and in subjects with a flat cochlear hearing loss.

METHODS

Subjects
In group I, 10 normal-hearing subjects participated (pure-tone hearing threshold not exceeding 10 dB HL at 500-8000 Hz): 4 females and 6 males. The subjects were between 20 and 30 years of age.
In group II, 12 subjects with a flat cochlear hearing loss (absolute slope not exceeding 10 dB/octave for 500, 1000, 2000 and 4000 Hz) between 25 and 70 dB HL participated: 6 males and 6 females. The subjects were between 17 and 83 years of age (mean 49 years).
All subjects were instructed to lie down on a bed in an acoustically insulated chamber and to sleep whenever possible.

General Outline

A filtered click stimulus of 1000 Hz with and without an appropriate high-pass masker was presented to each subject (explained below). Averaged responses were acquired at stimulus levels of 70 dB nHL and lower for the normal-hearing subjects and at 90 dB nHL and lower for the hearing-impaired subjects. The level was stepwise lowered until the major response peak disappeared. For each stimulus level the latency was measured and the difference in latency between stimulation with and without high-pass masking was calculated. Statistical analysis was done with the SPSS-X computer program.

Stimulation and Masking

The stimulus was generated by passing a click of 100 μs electrical duration through a bandpass filter with cut-off frequencies of 890 and 1120 Hz. The acoustical stimulus and acoustical spectrum are presented in Figure 1.

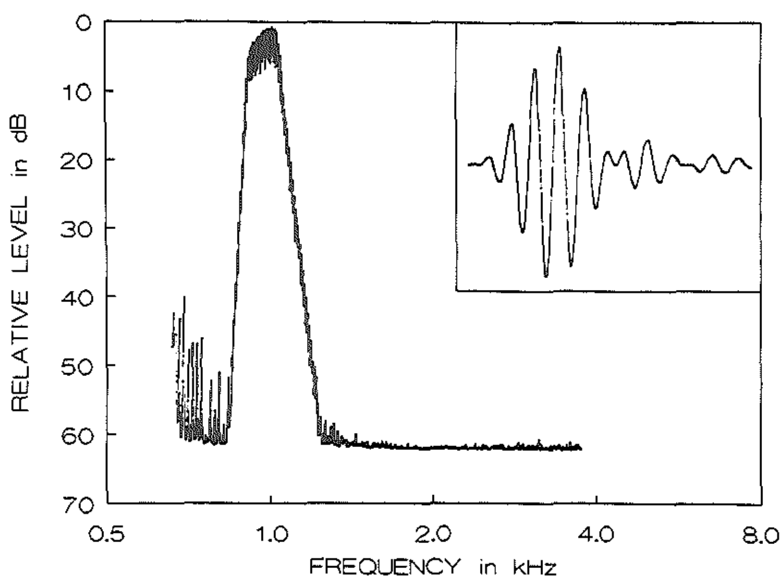

Figure 1
Spectrum and waveform (inset) of the 1000 Hz tonepip stimulus used in this study.

The stimulus envelope has an approximate rise-fall time of 3.5 ms with no plateau. The filter slopes were 135 dB/octave and the theoretical noise floor was 96 dB down (Kemo VBF/24), the actual noise floor was proven to be more than 65 dB. The stimulus repetition rate was 20 Hz with alternating polarity. The stimulus was attenuated (Hewlett Packard 350 D) with 10 dB steps well above ABR-threshold and with 5 dB steps near ABR-threshold. The levels for the stimulus are expressed in dB nHL and in dB RTL. 0 dB nHl was equivalent to 24 dB peSPL as measured via a

B&K 4153 artificial ear. dB RTL means relative to the ABR-threshold of each subject.
The stimulus was presented monaurally to the subject via a TDH39 headphone with MX-41/AR ear-cushions. For each stimulus level, the ABR to the same stimulus masked by high-pass noise was also recorded.
The noise masker was generated by a white noise generator (General Radio 1382). This noise was filtered by a filter (Kemo VBF/24, 135 dB/octave) used either as high-pass filter with a cut-off frequency of 1590 Hz or as all-pass filter. The latter mode resulted in a white noise masker. 0 dB nHL was equivalent to 24 dB SPL. With this white-noise masker, the appropriate masking level was chosen as the lowest level at which no ABR to a 60 dB nHL stimulus was found in the normal-hearing subjects (electrophysiologic masking); for the hearing-impaired subjects the stimulus level was raised to 90 dB nHL. A masker sensation level of 6 dB above the filtered click sensation level was in all cases sufficient to completely mask the ABR (S/N ratio -6 [dB peSPL-dB SPL]). The masker level was then locked to the filtered click level and the filter was set to the high-pass mode.

ABR Recording

Auditory brainstem responses were recorded with silver chlorided cup electrodes. A two channel recording was made, the positive input was connected to the subject's vertex and the negative inputs to the mastoid of the stimulated ear for ipsi-lateral recording and to the non-stimulated ear for contra-lateral recording. A forehead electrode was used for the zero-lead. Inter-electrode impedances were always kept below 3 kΩ.
The electrode signal was amplified 10^4 and band-pass filtered from 10 to 4000 Hz. The filter slopes were 24 dB/octave (Krohn-Hite 3322).
The electrode signal was averaged over 2048 sweeps that did not exceed $\pm$ 6.25 μV (artefact rejection). A time base of 15 ms was used.

ABR Identification

As our ABRs (Figure 2) resemble those described by Suzuki et al (1981[a]), we use their nomenclature and call the first positive peak P10 and the following negative trough N15. At near-threshold stimulus levels the responses were repeatedly measured to test replicability. The responses were judged by the first and second author. The lowest stimulus level at which P10/N15 could be replicated was scored as

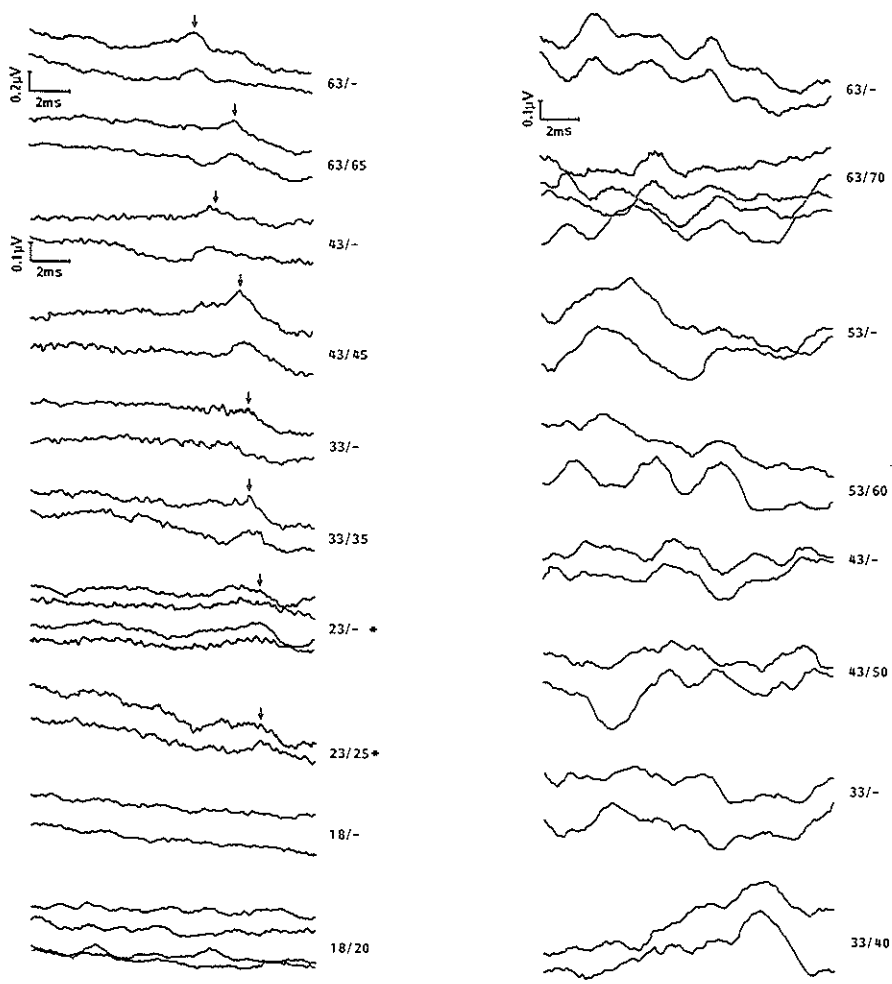

Figure 2a *Figure 2b*

Figure 2

Example of a low-frequency ABR which is classified as good: 2a, and one classified as bad: 2b. Stimulus and masking noise levels are given of each recording pair. Pairs are matched according to stimulus level, each pair consist of an ipsilateral recording (upper trace and a contralateral recording (lower trace), at and around threshold level (Fig 2a, 23/- and 18/20) replications can be seen. P10 is indicated with an arrow, ABR-threshold with an asterisk.

ABR-threshold.
The latency measurements were determined for the positive peak (P10) just prior to the negative trough (N15) (Figure 2).
Response quality was also scored. The response was marked "good" if P10 was clearly discernible and the baseline was more or less flat (Figure 2a). The response was marked "moderate" if P10 was discernible but some noise was present in the response and marked "bad" if P10 was hardly discernible (Figure 2b).It was also scored whether the subject slept during the recording session.

RESULTS

From the 10 normal-hearing subjects a total of 111 ABRs were recorded. The quality of the responses was scored as "good' in 87 cases, as "moderate" in 11 cases and was scored as "bad" in 13 cases. Sleep was noted during 83 recordings.
The relation between the quality of the responses and the arousal state is shown in Table II.

Table II
Cross table of response quality versus arousal state for subjects with normal hearing, number of ABR's are given.

	Sleep	No sleep	Total
Good	82	5	87
Moderate	1	10	11
Bad		13	13
Total	83	28	111

Table III
Cross table of response quality versus arousal state for subjects with cochlear hearing loss, number of ABR's are given.

	Sleep	No sleep	Total
Good	26	4	30
Moderate	2	28	30
Bad		16	16
Total	28	48	76

Unless specified otherwise the results for the normal-hearing subjects are derived from the "good" responses.
In 7 of the 10 normal-hearing subjects the ABR-threshold response quality was marked "good" for both stimulus conditions. The mean ABR-threshold of these subjects for the unmasked filtered click and for the high-pass masked filtered click was the same and amounted to 19 dB nHL (43 dB peSPL) with a standard error of estimate of 3.5 dB. The individual difference in ABR-threshold between both stimulus conditions did not exceed 5 dB, which equals one step in stimulation level.
From the 12 subjects with cochlear hearing loss a total of 76 ABRs were recorded. The relation between arousal state and response quality of the subjects with hearing

loss is shown in Table III. Unless otherwise specified and in contrast to the normal-hearing subjects the following results of the subjects with hearing loss are derived from both the "good" and "moderate" results.

In 9 of the 12 subjects, the ABR-threshold for both stimulus conditions was scored as "good" or "moderate". In 3 of these 9 subjects the ABR-threshold for the masked condition was 5 dB lower, in the other 6 no difference between masked and unmasked stimulus condition was found.

The pure-tone threshold at 1000 Hz had a mean value of 42 dB nHL, and a range of 20 to 60 dB nHL. The mean ABR-threshold for the unmasked stimulus conditions was 10 dB, and for the masked stimulus condition 12 dB above the mean pure-tone threshold. The correlation between pure-tone threshold at 1000 Hz and ABR-threshold of both stimulus conditions can be seen in Figure 3. The correlation coefficient is high and exceeds 0.8 (unmasked: 0.88; masked: 0.84). The standard error of estimate is 7 dB (unmasked 7.4, masked 6.9). The slope of the regression line is 1.4 for both stimulus conditions. (For calculation of standard error of estimate and regression line both variables are considered as dependent.)

For each stimulus level the latency of peak P10 was measured both for the ABR evoked by the unmasked filtered click and evoked by the high-pass masked filtered click as can be seen in Figure 2.

From these ABRs the latencies of P10 were measured for each stimulus level and for both stimulus conditions.

A latency-level function for the normal-hearing subjects was constructed as shown in Figure 4 (solid symbols). The latency difference between both stimulus conditions is substantial at high stimulus levels, but decreasing near ABR-threshold. Data of other authors are also shown (open symbols).

The latency difference at each stimulus level was calculated for each subject and is shown in Figure 5 as a function of stimulus level in dB RTL both for the normal-hearing subjects and for subjects with cochlear hearing loss.

For the normal-hearing subjects no latency difference is found up to 15 dB RTL. From 15 dB RTL on a gradually increasing latency difference is found. At moderate stimulus levels of 40 dB RTL the latency difference is approximately 2.0 ms.

For the hearing-impaired subjects, from ABR-threshold level onwards, a steep increase in latency difference takes place and after 20 dB a latency difference of approximately 2.0 ms is reached.

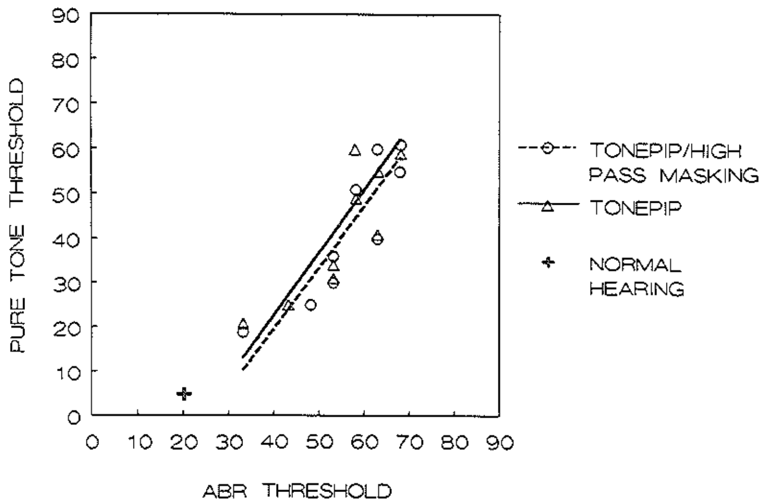

Figure 3
Scattergram of ABR-threshold for masked and unmasked 1000 Hz filtered click stimulation with pure tone threshold at 1000 Hz. Linear regression lines are shown, calculation was done regarding both variables as dependent. The mean ABR-threshold for normal hearing is also shown, the cross represents both the high-pass masked and the unmasked 1000 Hz filtered click evoked ABR-threshold which are equal.

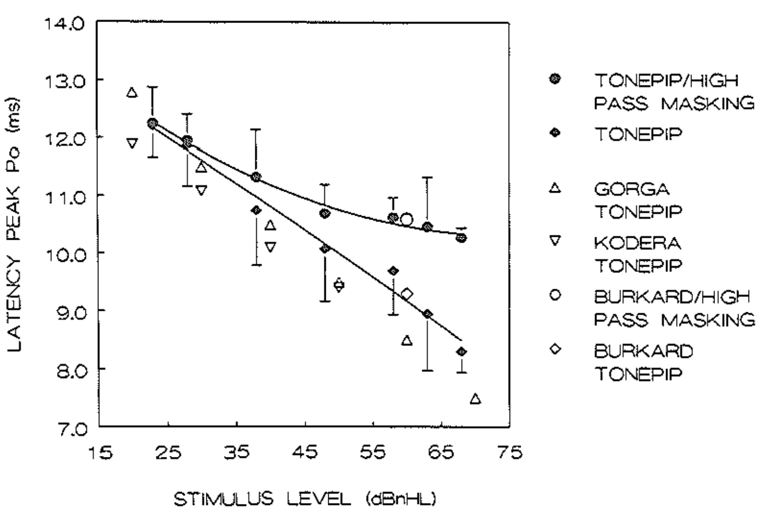

Figure 4
Mean latency level function for normal hearing subjects both for high-pass masked and non-masked 1000 Hz stimulated ABR (solid symbols), data of other authors are also shown (open symbols).

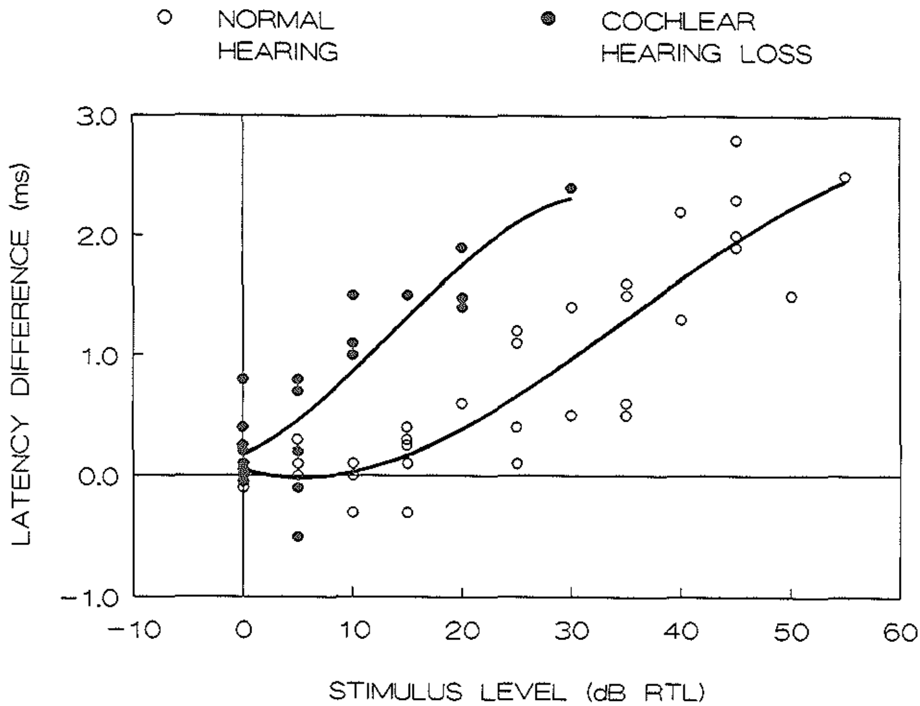

Figure 5

Scattergram and curve fitting of the latency difference of P10 between the high-pass masked and non-masked ABR in normal hearing subjects and in subjects with cochlear hearing loss as a function of stimulus level (dB RTL).

DISCUSSION

In the present study, the ABR-threshold to 1000 Hz filtered clicks with a rise-fall time of 3.5 ms amounted, for normal-hearing subjects, to 19 dB nHL (43 dB peSPL) with a standard error of 3.5 dB. This is in the same range as reported by other authors: Kodera et al. (1977[b]) reported an ABR-threshold to 1000 Hz tonebursts of 16.5 dB SL. Drug induced sleep was used on all subjects. Beattie and Boyd (1985) reported an identifiable P10 and N15 to a 1000 Hz toneburst (4 ms rise-fall time, 1 ms plateau) at a stimulus level of 20 dB nHL in 50% of normal-hearing subjects.

For the subjects with cochlear hearing loss, the mean ABR-threshold for the unmasked stimulus conditions is 10 dB and for the masked stimulus condition 12 dB above the mean pure-tone threshold. These values are less than the 19 dB above pure-tone threshold in the normal-hearing subjects. This is also represented by the

slope of the regression line (Figure 3) which is 1.4. When the normal-hearing subjects are taken into account as well, the slope of the regression line is 1.1. This somewhat curved relation between ABR-threshold and pure-tone audiogram in this range of hearing loss can be found for click stimulated ABR-thresholds as well (van der Drift et al., 1987, Figure 7) and is probably caused by loss of temporal integration (Gorga et al., 1984) and an abnormal loudness growth (recruitment).
The correlation between pure-tone threshold at 1000 Hz and ABR-threshold (Figure 3) is high for both stimulus conditions and exceeds 0.8 (unmasked: 0.88; masked: 0.84) with a low standard error of estimate of 7 dB (unmasked 7.4, masked 6.9). This high correlation between pure-tone threshold at 1000 Hz and the ABR-threshold to 1000 Hz filtered clicks does, however, not in itself indicate a good frequency-specificity, because only subjects with a flat pure-tone audiogram were selected, to exclude that the latency of the unmasked stimulus condition could be influenced by the shape of the pure-tone audiogram. The correlation coefficient and standard error of estimate of the ABR-threshold with the pure-tone threshold of the other frequencies are therefore equally good.

The latency-level function of the unmasked filtered click for the normal-hearing subjects can be seen in Figure 4, together with data of other authors who used brief tonal stimulation. Although a comparison with data of other authors is hazardous because of the different stimulus parameters (Kodera et al., 1977[b]; Burkard and Hecox, 1983 see Table I; Gorga et al., 1988, digitally generated tonebursts (Hanning window) rise-fall time 2 ms), there is a general agreement between our latency-level function of the unmasked stimulus and the data of the other authors. The latency level function of the masked stimulus condition is different, however, from the unmasked stimulus condition. This difference will be discussed below.

Tables II and III clearly demonstrate the importance of being asleep in obtaining a good quality low-frequency-specific ABR. Sleep reduces the muscle artifact. Muscle artifact has a peak amplitude near a frequency of 60 Hz (Hayes, 1960). This is probably in the same frequency region as the low-frequency-specific ABR (Takagi et al., 1985). Muscle artifact can therefore completely obscure the low-frequency-specific ABR.

We observed an interesting phenomenon in the majority of our normal-hearing subjects and in some of the hearing-impaired subjects: around the stimulus level of

30 dB RTL, peak P10 seems to fade away when the stimulus without masking was used (Figure 2, 43 dB nHL stimulus level). Near this level a sharp increase in latency takes place which probably causes a flattening of peak P10 which makes it more difficult to discern.
Although no formal response growth analysis is done, we consider this important enough to mention, because if one is not aware of this fact and if the responses are "noisy", it is quite possible that this response-level is mistaken as ABR-threshold level.

As stated in the introduction, the brief tonal stimulus without masking is a disputed low-frequency-specific stimulus. Although some authors report a good correlation with the pure-tone audiogram in clinical studies, the definite proof has yet to be given because in most applicable studies the number of patients is small (Kodera et al., 1977[b]) and both the steepness of the pure-tone audiogram and the dynamic range of the pure-tone hearing losses are not sufficiently documented to draw certain conclusions (Kobayashi et al., 1985; Hawes and Greenberg, 1981; Davis et al., 1985; Yamada et al., 1983; Suzuki and Horiuchi, 1977; Hayes and Jerger, 1982).
On the other hand, some authors state that the brief tonal stimulus is not low-frequency-specific. However, some of these studies do not meet the prerequisites for a good low-frequency-specific ABR as described in the introduction: the lack of frequency-specificity could be attributed in some studies to inadequate response filtering (Kinarti and Sohmer, 1982; Kileny, 1981) or to the fact that the subjects were not asleep (Hayes and Jerger, 1982).
But other reports strongly support the view of lack of low-frequency-specificity by comparing the ABR-latency evoked by a brief tonal stimulus with the ABR-latency of the same stimulus masked with high-pass noise (Beattie and Boyd, 1985; Burkard and Hecox, 1983; Laukli and Mair, 1986; Jacobson, 1983). In these studies, a considerable latency delay is found when the stimulus is masked by high-pass noise as can be seen in Figure 4 for the data of Burkard and Hecox (1983) who masked a 1000 Hz toneburst with 2000 Hz high-pass noise. Although experiments which used masking do not always report useful responses there is no evidence that responses can be elicited from regions in the cochlea which are adequately masked.
The above-mentioned authors conclude, therefore, that brief tonal stimulation is thus not frequency-specific, at least the stimulus used in these studies is not. The stimulus level in these studies is far above ABR-threshold level. In the introduction we hypothesized that frequency-specificity is better near ABR-threshold level. Our

results indeed support this hypothesis. In Figure 4, the latency difference for the normal-hearing subjects between masked and unmasked stimulus condition is substantial at high stimulus levels but decreasing as stimulus level decreases. To assure that the masked response is indeed originated from below the 1590 Hz region on the basilar membrane, the masking noise level was chosen by electrophysiologic means. This masking noise level is perhaps higher than necessary (Stapells, 1984) but was chosen to prevent undermasking. In Figure 5, the latency difference is shown as a function of stimulus level relative to the ABR-threshold level. For levels up to 15 dB above ABR-threshold level, the latency difference is 0 ms. This means that if the effective stimulation is equal, both stimulus conditions elicit ABRs from the same basilar membrane region. That the effective stimulation is equal for both stimulus conditions can be concluded from the fact that the ABR-threshold level is equal.
Therefore we conclude that the 1000 Hz filtered click used in this study is indeed frequency-specific at ABR-threshold level in the normal-hearing subjects.

The latency-difference level relation of the hearing-impaired subjects shows a similar pattern as in the normal-hearing subjects (Figure 5), although in some aspects different. At stimulus levels far above ABR-threshold the latency difference between both stimulus conditions is substantial but at ABR-threshold there is little or no difference.
Following the same argument as for the normal-hearing subjects we conclude that the 1000 Hz filtered click used in this study is indeed frequency-specific at ABR-threshold level not only in the normal-hearing subjects but also in the subjects with a flat cochlear hearing loss.

Although the stimulus used in this study is frequency-specific at ABR-threshold level, above ABR-threshold, the latency of the unmasked stimulus condition is shortening in comparison with the masked condition and the latency difference is thus increasing with increasing stimulus level (Figure 5). This indicates a stimulation of higher frequencies by the unmasked stimulus. In our data the latency difference, for the normal-hearing subjects, at approximately 45 dB RTL is 2.0 ms. From the data of Van Zanten (1984) who used notched noise masking, a latency difference of 2.0 ms between 1000 and 4000 Hz elicited ABRs can be calculated. Therefore it is likely that the frequency region which is excited at approximately 45 dB RTL seems to be the 4000 Hz region.

The mechanism which causes this suprathreshold upward spread of the stimulus is not likely to be related to the physical properties of the stimulus, like a "sideband" mechanism. As can be seen in Figure 1, our stimulus is narrow and has no effective sidebands. The upward spread of excitation probably represents the frequency-selective properties of the cochlea. Because of the asymmetry of the travelling wave a low-frequency-specific stimulus can activate higher frequency regions. These higher frequency regions are triggered before the stimulus reaches the low-frequency part of the cochlea, are better synchronized and somehow "overrule" the later and less synchronized response from the low-frequency regions. This mechanism is represented by the low-frequency tail of the tuning curves (Figure 6).

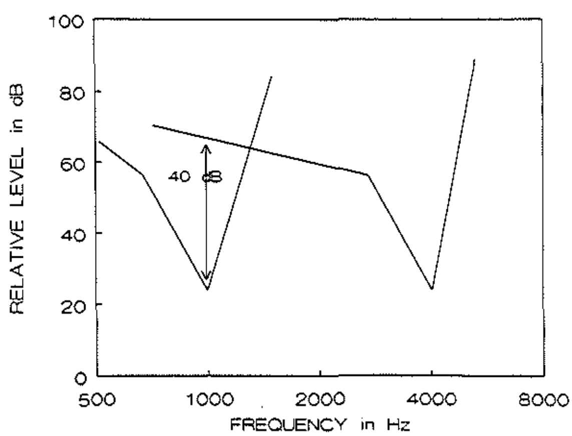

Figure 6
Schematical tuning curves for tonepip stimulation derived from data of Eggermont 1977 for normal hearing subjects.

These tuning curves are schematically redrawn from Eggermont (1977) and were measured by electrocochleography and tone-on-tone masking. A difference between the tip of the 1000 Hz region and the low-frequency tail of the 4000 Hz region of 40 dB can be deduced for the normal-hearing subjects (Figure 6). This corresponds well with the difference between 1000 and 4000 Hz in our normal-hearing subjects, of 45 dB, as stated above.

This also means that the maximum difference in low-frequency hearing loss between 1000 and 4000 Hz which can be detected using the unmasked brief tonal stimulus cannot exceed approximately 40 to 50 dB in subjects with a normal frequency-

selectivity. This can also be demonstrated psychophysically in some subjects (Thornton and Abbas, 1980).
In the subjects with cochlear hearing loss, the latency-difference level function (Figure 5), however, is in some aspects different from that in the normal-hearing subjects (Figure 5). Already at 10 dB RTL a latency difference can be observed, at 20 dB RTL a latency difference of 2.0 ms is found and thus stimulation of the 4000 Hz region occurs at this rather low stimulus level.
This can be explained by a loss of frequency-selectivity.

In Figure 7, hypothetical tuning curves of fibres of 1000 and 4000 Hz are constructed for diminished frequency-selectivity.

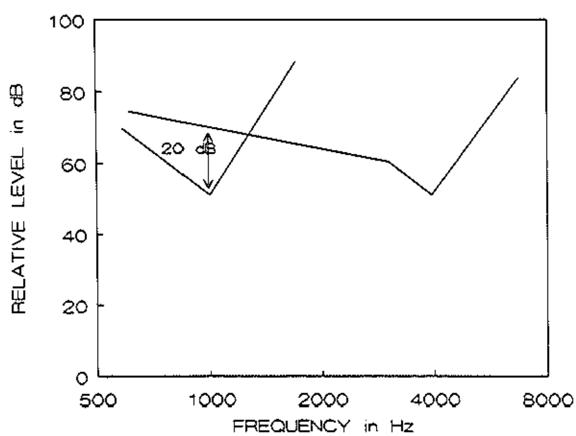

Figure 7
Hypothetical tuning curves for tonepip stimulation for subjects with cochlear hearing loss and degraded frequency-selectivity.

When frequency-selectivity diminishes as in cochlear hearing loss, a much broader tuning curve is found with loss of the sharp tip (Eggermont 1977). This is also found in single fibre tuning curves in pathological ears (Kiang et al., 1976; Evans 1974). Therefore, the difference between the tip of the 1000 Hz fibers and the low-frequency tail of the 4000 Hz fibres is smaller. This probably explains the latency-difference level function of the subjects with hearing loss (Figure 5).
This implies that the maximum difference in low-frequency hearing loss between 1000 and 4000 Hz which can be detected using the unmasked brief tonal stimulus can be as low as 20 dB in subjects with a poor frequency-selectivity.

As can be concluded from the latency-difference level function in the subjects with cochlear hearing loss (Figure 5), an "ABR-threshold" of 15 dB above the real ABR-threshold means an ABR-threshold which is perhaps not frequency-specific. This emphasizes again the importance of finding the lowest possible ABR-threshold and thus the importance of the best signal-to-noise ratio.

Our results also imply that if one is not satisfied with the frequency-selectivity of the ABR evoked by a brief tonal stimulus, then a masking noise level of 20 dB below electrophysiologic masking level is sufficient to guarantee that the ABR is indeed originating from the 1000 Hz region in subjects with normal-hearing and a presumably normal frequency-selectivity (Figure 5). A level of not less than 10 dB below electrophysiologic level, however, is necessary in subjects with unknown and thus perhaps poor frequency-selectivity (Figure 5).
On the other hand, masking noise might leak energy into the intended region of stimulation in case of bad frequency-selectivity (Gorga and Worthington, 1983). This would increase the ABR-threshold in that region. On the basis of our results, this leaking of masking noise cannot completely be excluded because the ABR-threshold of the masked condition is 5 dB worse in 3 out of 9 cases. But if any effect from masking noise is present it is minimal. This is consistent with the literature. Beattie and Boyd (1985) used white noise and notched noise to mask the toneburst. They did not find any difference in detectability of P10 or N15 compared to the no noise condition, although the levels of the masking noise were considerably below the toneburst level.

The 1000 Hz filtered click stimulus used in this study is frequency-specific at ABR-threshold level both in the normal-hearing subjects and in the subjects with a flat cochlear hearing loss. Because the stimulus range in which a frequency-specific response can be elicited is small in the subjects with a flat cochlear hearing loss compared with the normal-hearing subjects (Figure 5), further research is necessary to investigate the frequency-specificity of the 1000 Hz filtered click in patients with a steep hearing loss, both high-frequency- and especially low-frequency in character.

CONCLUSIONS:

1. The 1000 Hz filtered click employed in the present study elicits frequency-specific responses at ABR-threshold level in normal-hearing subjects and in those with a flat cochlear hearing loss.
2. The frequency-specificity of the 1000 Hz filtered click employed in the present study is degrading from 15 dB RTL in normal-hearing subjects and from 5 dB RTL in subjects with a flat cochlear hearing loss.
3. Sleep, which improves signal to noise ratio, is a prerequisite for low-frequency-specific ABR-threshold detection.
4. High-pass masking does not greatly influence the ABR-threshold detectability in a negative sense.
5. A further investigation of frequency-specificity of the 1000 Hz filtered click in patients with a steep cochlear hearing loss is needed.

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CHAPTER V

LOW-FREQUENCY-SPECIFICITY OF THE AUDITORY BRAINSTEM RESPONSE THRESHOLD ELICITED BY CLICKS MASKED WITH 1590 HZ HIGH-PASS-NOISE IN SUBJECTS WITH SLOPING COCHLEAR HEARING LOSSES

ABSTRACT

In this study the frequency-specificity of the ABR-threshold to a click masked with 1590 Hz high-pass-noise was determined in subjects with sloping cochlear hearing losses both high- and low-frequency in character. The results show that the ABR-threshold elicited by this stimulus is low-frequency-specific. The standard error in estimating the 1000 Hz pure-tone threshold from the high-pass-noise-masked click evoked ABR-threshold is 10.2 dB which equals that for estimating the 3000 Hz pure-tone threshold from the routinely used unmasked click evoked ABR-threshold (van der Drift et al., 1987). The ABR-threshold elicited by a click masked with 1590 Hz high-pass-noise can therefore be regarded as an accurate tool to predict the pure tone hearing loss at 1000 Hz. However, this method is less suitable for routine clinical testing because of the needed masking noise: the occasional high loudness level adversely affects the response quality and reduces the dynamic range of pure-tone hearing losses to be assessed. A third disadvantage is that determining the masking level electrophysiologically for each ear is time consuming. The search for a method with no or less masking noise should therefore continue.

RESUMÉ

Chez les sujets normaux et les patients présentant avec une surdité sensorielle avec un audiogram incliné positivement ou négativement, la spécificité fréquentielle est déterminé du seuil du potential évoqués du tronc cérébral par un clic au fond d'un bruit masquant les fréquences au dessous de 1.59 kHz. Les résultats montre que ce seuil est spécifique en fréquences bas. L'écart-type de la détermination du seuil d'audiogramme a 1 kHz par le seuil objective est 10.2 dB. C'est égal a l'écart-type de la détermination du seuil d'audiogramme a 3 kHz par le seuil du potential évoqués du tronc cérébral par un clic non-masqué de routine (Van de Drift et al, 1987). Donc le seuil objective spécifique en fréquences bas est qualifié pour détermination de la mesure de la surdité a 1 kHz. Mais cette méthode est moins agréable parce que le bruit masquant: la niveau haute du son quelquefois nuit a la qualité de la résponses électro-physiologique et réstreint la dynamique de la surdité a mésurer. Un troisieme désavantage est la détermination électro-physiologiquement de la niveau de la bruit masquant qui prend de temps long. La recherche d'une méthode avec moins de ou entierement sans bruit masquant doit continuer.

INTRODUCTION

A low-frequency (500 and 1000 Hz) specific auditory brainstem response (ABR) threshold can be an important addition to the standard click evoked ABR-threshold, because the click evoked ABR-threshold corresponds with the higher frequencies (2000-

4000 Hz) in the pure-tone audiogram only. Two major approaches for obtaining low-frequency-specific ABRs can be discerned. One approach, the use of brief tonal stimulation is discussed elsewhere in detail (Conijn et al., 1990b).
This article focuses on the other major approach: the use of masking noise to isolate frequency-specific response area's in the cochlea.

Three strategies of masking are commonly employed:

1. The use of high-pass masking-noise.
2. The use of notched noise masking in which a notch is made by using both high- and low-pass masking-noise.
3. The derived response technique which is an extension of the high-pass masking-noise paradigm.

The stimulus which is used to elicit the ABR is commonly a click or a brief tonal stimulus. The brief tonal stimulus has the advantage that more energy is concentrated in the desired frequency range and thus the necessary masking noise level is less than with click stimulation. The click stimulus is, however, easy to generate, is standard on all ABR equipment and gives an excellent responses because of its good synchronicity.

The masking theory is based on three assumptions:

1. The masking noise can prevent the generation of an ABR.
2. The masking noise can be restricted to a certain frequency-specific region.
3. The minimal necessary masking noise level is linear with the stimulus level.

That masking noise can prevent the generation of the ABR, when the noise level exceeds a specific stimulus level, seems undisputed, although the effectiveness of masking can be diminished in ears with cochlear damage (Gorga and Worthington, 1983). The possible mechanism by which masking noise presumably inhibits a synchronous response of nerve fibres is that noise will generate random responses which are not time locked to the onset of the click stimulus.

The assumption that the masking noise is restricted to a desired area is, however, questionable. Filtered noise is, as any other stimulus, submitted to the frequency-selective properties of the cochlea. It is this frequency-selective property that restricts the noise to a certain frequency domain (assuming a very steep slope of the noise filter). Therefore both high- and low-pass-noise will spread out to a certain extent. But because

of the asymmetry of the travelling wave, upward spread of low-pass masking-noise is much more likely to occur than the reverse. This upward spread especially occurs when frequency-selectivity diminishes as for instance in cochlear hearing loss (Wightman et al., 1977). The use of low-pass-noise is therefore hazardous because it can easily spread upwards and mask the stimulus.
The use of low-pass-noise is perhaps not necessary at all for generating a low-frequency-specific stimulus: when a brief tonal stimulus is used to elicit the response, then this brief tonal stimulus is submitted to the same frequency-selective properties of the cochlea and thus tends to spread out to higher frequency regions but not easily to lower ones (Conijn et al., 1990b). When a click is used to elicit the response, then this click also corresponds with higher frequency regions and probably does not tend to "spread out" to lower frequency regions.

But it is also inevitable that high-pass masking-noise spreads downward especially in the lower frequencies as described by Evans and Elberling (1982). Although this downward spread is weaker than the upward spread of the low-pass masking-noise and is probably not enough to cause unreliable ABRs.

The assumption that the masking noise is linear with the stimulus seems undisputed (Burkard and Hecox, 1983)

One of the difficulties encountered in masking techniques is the choice of the right masker level. Undermasking will result in an ABR which is not frequency-specific. Overmasking will artifactually elevate the ABR-threshold, will decrease the dynamic range in which stimulation is possible, is uncomfortable for the patient and gives a greater spreading of the masking noise. Another danger of high level masking noise is the induction of a temporary threshold shift.
Electrophysiologic masking, which is defined as the masking level just sufficient to mask the ABR, is considered necessary for adequate masking of the click stimulus. Unfortunately the electrophysiologic masking level is not the same for every subject and even not for each ear and therefore has to be determined for each ear, which is a time consuming procedure.
The masking level used with brief tonal stimulation is often 15 to 25 dB less than electrophysiologic masking level (Picton et al., 1979; Stapells, 1984; Beattie and Boyd, 1985). With these relatively low masking levels much of the drawbacks of masking noise are eliminated. But as stated below this procedure has a different aim.

Van Zanten and Brocaar (1984), Pratt and Bleich (1982) reported on clicks in notched noise in normal-hearing subjects with contradicting results. In a later report Pratt et al. (1984) also reported on 10 subjects with hearing loss. No correlation between ABR-threshold and pure-tone threshold could be found. The reasons for the contradicting data could be due to different stimulus parameters and the use of the low-pass-noise. Pratt used a notch of 1/2 octave wide and van Zanten of 5/3 octave wide, the relative small notch width of Pratt together with the splatter of the low-pass noise did perhaps mask the frequency-specific response.

Picton et al. (1979), Stapells (1984) Stapells et al (1990) and Beattie and Boyd (1985), used brief tonal stimuli in notched noise. With this method low-frequency-specific responses are reported but most studies are done with normal-hearing subjects or a limited number of subjects with hearing loss. Furthermore, these authors used masking noise 15-25 dB below electrophysiologic masking level. The low-level masking noise is only intended to mask the spectral splatter and is not intended to contribute to the frequency-specificity of the stimulus itself. Therefore the results are perhaps for a large part due to the frequency-specific properties of the brief tonal stimuli alone (Conijn et al., 1990b).

Don et al. (1979) and Eggermont and Don (1982a) used the derived response technique with good results although a large series of subjects with sloping cochlear hearing loss is not reported.

In the derived response technique, two responses are subtracted which are masked by high-pass masking-noise with different cut-off frequencies. It is based on the assumption that these responses differ only in the contribution of the frequency region between the cut-off frequencies of the maskers. Therefore the subtracted response originates from this limited frequency region only. Although this assumption seems valid (Parker and Thornton, 1978), this method is time consuming, needs computer storage and because of the substraction of two responses decreases the signal to noise ratio of the response with a factor $\sqrt{2}$.

Furthermore the contribution of the region at and below 500 Hz to the ABR to clicks is probably minimal (Don and Eggermont, 1978; Don et al., 1979; Thümmler et al., 1981; Laukli et al., 1988; Gorga et al., 1988).

The above implies that for a 1000 Hz frequency-specific stimulus high-pass masking-noise alone is sufficient and that the low-pass band of the notched noise is hazardous and the derived response technique is time consuming.

Therefore a two-point ABR-audiogram consisting of a high-frequency point (2000-4000 Hz) obtained with the normal click stimulus and a 1000 Hz ABR-threshold obtained by masking the click with high-pass-noise as proposed by Eggermont (1982b) seems the best approach.

Laukli et al. (1988) used 500 Hz brief tonal stimuli (rise/fall time 2 periods and 1 period plateau) in 1000 Hz high-pass masking-noise. He concluded that this was not a reliable method for routine assessment of low-frequency ABR-threshold. Fjermedal and Laukli (1989) reported that the 1000 Hz brief tonal stimulus (rise/fall time 2 periods and 1 period plateau) in 2000 Hz high-pass masking-noise was only "slightly better". In contrast Debruyne (1984) used a single sine wave of 1000 Hz with 2000 Hz high-pass masking-noise and a single sine wave of 4000 Hz as stimuli. In 23 patients the slope of the audiogram between 1000 and 4000 Hz was compared with the slope of the ABR-threshold between the 1000 Hz high-pass-noise-masked and the 4000 Hz stimulus. A rather good agreement was found both in high- and low-frequency hearing loss.
The difference between the studies of Debruyne on the one hand and Laukli and Fjermedal on the other hand can perhaps be attributed to the differences in stimulus. Debruyne used a single sine wave stimulus and perhaps this "click like" stimulus gives a better synchronisation and thus a better response.
In an earlier report (Conijn et al., 1990a) clicks with high-pass masking-noise with a cut-off frequency of 1590 Hz were used in normal-hearing subjects. A reliable ABR-threshold at approximately 20 dB nHL could be obtained with a latency at ABR-threshold level of approximately 11 ms which indicates that the responses are generated in the apical region.

In conclusion the masking technique seems valid in normal-hearing subjects but is not validated in subjects with hearing loss especially in subjects with sloping cochlear hearing loss.
Therefore the following experiment was done:

> The ABR elicited by clicks masked with high-pass-noise with a cut-off frequency of 1590 Hz was studied in patients with sloping cochlear hearing losses both high- and low-frequency in character.

METHODS

Subjects

Forty-nine hearing-impaired subjects were tested. Their pure-tone thresholds (PTTs) were measured for 250, 500, 1000, 2000, 4000 and 8000 Hz. Subjects with sloping cochlear hearing losses both high- and low-frequency in character and with normal tympanic membranes were included in this study. A hearing loss is defined as sloping if an absolute difference in PTT between 1000 and '3000' Hz (mean 2000 and 4000 Hz) of 20 dB or more exists. The '3000' Hz frequency was chosen because this is the frequency of maximum correspondence of the unmasked click. Also 4 subjects were included with a pure-tone hearing threshold better than 15 dB for 500 to 4000 Hz from an earlier study (Conijn et al., 1990a). This was done to increase the dynamic range of losses and to enable comparison with other data. In total 53 subjects were studied: 38 males and 15 females, thirty eight with a high-frequency hearing loss, 11 with a low-frequency hearing loss and 4 with no hearing loss. The subjects were between 11 and 88 years of age, mean age 56. In the high-frequency hearing loss group the cause of the hearing loss was in most cases presbyacusis and noise induced hearing loss, in the low-frequency hearing loss group the cause was in most cases congenital and Meniere's disease.

The subjects were instructed to lie down on a bed in an acoustically insulated chamber and to relax. The arousal state of the subject was scored as sleep or no sleep. The probable cause of the cochlear hearing loss was scored and the appearance of the tympanic membrane.

The stimulus was presented monaurally to each subject via a TDH 39 headphone with MX-41/AR ear-cushions.

Stimulation and Masking

A click stimulus was generated with alternating polarity and an electrical duration of 100 μs at a repetition rate of 20 Hz. The stimulus levels for the click are expressed in dB nHL which means relative to the mean behaviourial threshold in normal-hearing subjects. By calibration via an artificial ear (B&K 4153) 0 dB nHL was found to be equivalent to 34 dB peSPL. All click levels mentioned below are unmasked click levels even if the click was masked. The masker was generated by a white noise generator (General Radio 1382). This noise was passed through a filter (Kemo VBF/24, 135 dB/octave) used either as a high-pass filter or as an all-pass filter. The latter mode resulted in a white-noise masker, 0 dB nHL was equivalent to 24 dB SPL. With this

white-noise masker the appropriate masking level was determined electrophysiologically as the lowest masking level at which no replicable peak was found in the ABR to a 70 dB nHL click level or upto 85 dB nHL, urged by the amount of hearing loss. The masker level was usually 15 dB above the click level with a range of 10 to 25 dB. The masker level was then locked to the click level and the filter was switched to the high-pass mode with a cut-off frequency of 1590 Hz. The value of 1590 Hz is chosen because it corresponds with previous research (van Zanten and Brocaar, 1984), but is in essence somewhat arbitrarily.
The high-pass-masked-click was attenuated (Hewlett Packard 350 D) in 10 dB steps well above ABR-threshold and in 5 dB steps near ABR-threshold.

ABR Recording

ABRs were recorded with chlorided silver cup electrodes. A two channel recording was made, the positive input was connected to the subject's vertex and the negative inputs to the mastoid of the stimulated ear for ipsi-lateral recording and to the non-stimulated ear for contra-lateral recording. A forehead electrode was used for the zero-lead. The inter-electrode impedances were kept below 3 kΩ.
The response was amplified 10^4 times and band-pass filtered from 10 to 3000 Hz. The filter slopes were 24 dB/octave (Krohn-Hite 3322).
The response was averaged over 2048 sweeps that did not exceed ± 6.25 μV (artifact rejection). A time base of 15 ms was used.

ABR Identification

As our ABRs resemble those described by Suzuki et al (1981) we also use their nomenclature and call the first positive peak P10 and the following negative trough N15. At stimulus levels near the ABR-threshold the responses were repeatedly measured to test replicability. The responses were judged by the first and second author. The lowest stimulus level at which P10/N15 could be replicated was scored as ABR-threshold.
The latency measurements were determined for the positive peak (P10) or the edge of the negative slope (N15).
Response quality was also scored. The response was marked "good" if P10 was clearly discernible and the baseline was more or less flat (Figure 1a). The response was marked "moderate" if P10 was discernible but some noise was present in the response (Figure 1b) and marked "bad" if P10 was hardly discernible.

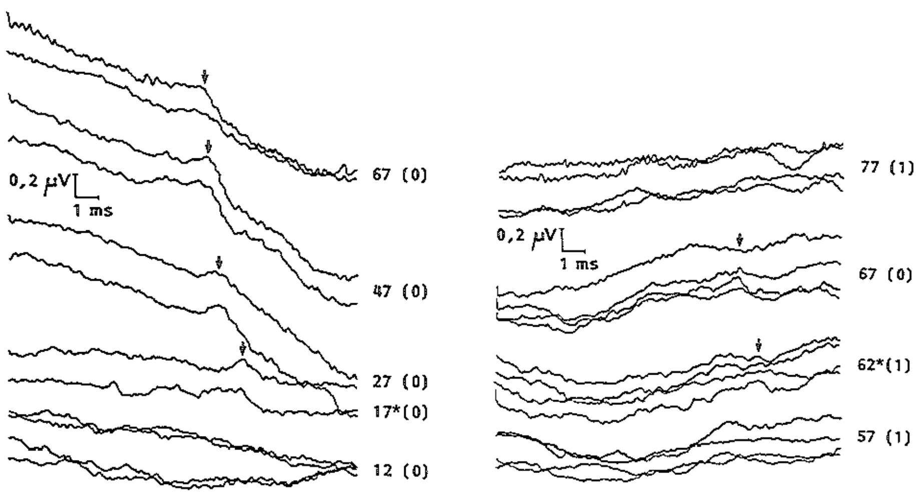

Figure 1a *Figure 1b*

Figure 1

Example of a series of auditory brainstem responses elicited by a click masked with 1590 Hz high-pass noise. Figure 1a of a normal hearing subject, figure 1b of a subject with 40 dB cochlear hearing loss at 1000 Hz. The stimulation level is given in dB nHL with each response pair, at the lowest stimulus level of Figure 1a and in all cases of Figure 1b replications were made, therefore at these recording levels the top two responses are the ipsi- and the two lower ones the contra-lateral tracings. The response quality is indicated between brackets (0="good", 1="moderate"). The response peak is indicated with an arrow and the ABR threshold is indicated with an asterisk.

Data Processing

The mean pure-tone hearing loss at the frequencies 500-4000 Hz, the mean absolute difference of the pure-tone hearing loss between 1000 and '3000' Hz and the mean ABR-threshold are reported. The relation between ABR-threshold and the various frequencies of the pure tone audiogram is reported with regard to the mean difference, standard deviation, correlation coefficient, slope of the regression line and standard error of estimate. For calculation of standard error of estimate and of the regression line both variables were considered as dependent because both were acquired with about equal measurement error. The pure-tone thresholds at the frequencies '1500' and '3000' Hz are the calculated means of those for 1000 and 2000 Hz and of those for 2000 and 4000 Hz, respectively. Statistical analysis was done with the SPSS-X computer program.

RESULTS

In all 53 patients the quality of the responses was scored. In 29 patients the arousal state was scored. The relation between the quality of the responses and the arousal state is shown in Table I.

Table I

Cross table of quality of the ABR-threshold against arousal state. The figures between square brackets represents the number of subjects where at the maximum stimulus level which was tolerated by the subject no response could be seen. The figures between round brackets represent the number of subjects where in retrospect the stimulus level was not adequately lowered down to the real ABR-threshold.

Quality	Arousal State			Total
	Sleep	No sleep	Not scored	
Good	6 [2]	2	13	21 [2]
Moderate	3	6(2)[1]	8(1)	17(3)[1]
Bad	1	3(1)[1]	1(2)	5(3)[1]
Total	10 [2]	11(3)[2]	22(3)	43(6)[4]

In 4 subjects no ABR-threshold could be obtained because at the highest stimulus level which could be tolerated by the patients no response could be seen, in some cases even the noise masking at a level of 90 dB nHL could hardly be tolerated; this means a click level of not more than 75 dB nHL. In six subjects no reliable ABR-threshold could be scored. In 3 cases this was due to bad response quality and in another 3 due to the fact that at the time of response judgment the stimulus level appeared not to have been lowered down to a level at which no ABR could be seen at the time of examination.

Unless specified otherwise the following results are derived from both the good- and moderate quality responses. This resulted in an ABR-threshold of 8 subjects with a low-frequency hearing loss (LFHL), 26 subjects with a high-frequency hearing loss (HFHL) and 4 subjects with no hearing loss (NHL).

The mean, range and standard deviation of the pure-tone hearing loss, of the ABR-threshold and of the *absolute* difference between 1000 and '3000' Hz are shown in Table II.

In Table III the data for the ABR-threshold across frequencies are summarized.

Table II

Mean, range and standard deviation of the pure tone hearing losses, of the ABR-threshold (ABR-T) and of the absolute difference between 1000 and '3000' Hz (DIFF). The figures for mean and range of the pure tone hearing losses are given in dB HL, the figures for the mean and range of the ABR-threshold are given in dB nHL, all other figures are given in dB.

	Pure-tone Frequency (Hz)							
	500	1000	'1500'	2000	'3000'	4000	ABR-T	DIFF
Mean	30	30	34	37	46	54	47	27
Range	0 - 65	0 - 65	0 - 73	0 - 85	0 - 98	0 - 120	17 - 72	-43 - 63
St.dev	19.5	18.7	17.8	22.9	26.7	32.5	15.7	26.3

Table III

Statistical data on the relation between the ABR-threshold and the various frequencies of the pure-tone threshold. Mean difference between pure tone threshold at that frequency and ABR-threshold; Standard deviation of this difference; Correlation coefficient; Slope of the regression line and Standard error of the estimate are given respectively. (Residual variance of the estimation of the 1000 Hz threshold is significantly less than that of all other thresholds except 1500 Hz, (p<0.02).)

	Pure-tone Frequency (Hz)					
	500	1000	'1500'	2000	'3000'	4000
Mean difference (dB)	17.2	16.4	13.0	9.5	1.0	-8.0
St.dev of difference (dB)	14.3	10.8	11.4	19.8	23.8	29.9
Correlation coefficient	0.68	0.81	0.77	0.53	0.46	0.23
Slope of regression line	1.3	1.2	1.2	1.8	2.2	4.4
St.error of estimate (dB)	13.0	10.2	10.8	16.6	19.0	21.4

In Figure 2a the scattergram of the ABR-threshold for the click masked by high-pass-noise with the pure-tone hearing loss at 1000 Hz is shown. Correlation coefficient is 0.81, the standard error of estimate is 10.2 dB and the slope of the regression line is 1.2.

In Figure 2b the scattergram of the ABR-threshold for the click masked by high-pass-noise with the pure-tone hearing loss at '3000' Hz is shown. Correlation coefficient is 0.46, the standard error of estimate is 19.0 dB and the slope of the regression line is 2.2.

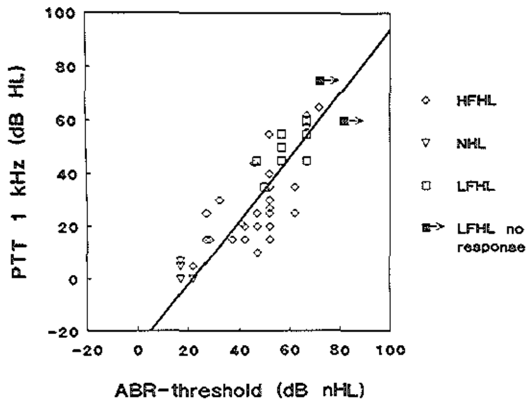

Figure 2a

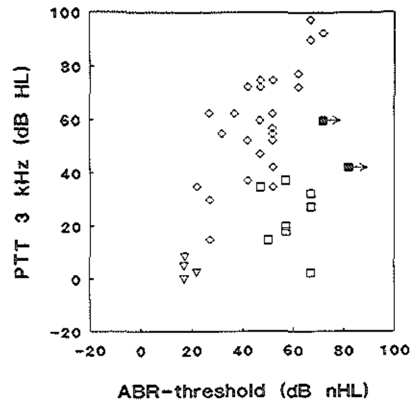

Figure 2b

Figure 2

Scattergram of the ABR-threshold evoked by a click masked with 1590 Hz high-pass noise against the pure-tone threshold at 1000 Hz (Figure 2a) and against the pure-tone threshold at 3000 Hz (Figure 2b). Solid line represents the regression line. HFHL: high-frequency hearing loss; NHL: no hearing loss; LFHL: low-frequency hearing loss; LFHL no response: highest stimulus level which was tolerated by the subject is given as ABR-threshold level although no response could be seen due to severe hearing loss (These subjects were not included in statistical analysis).

DISCUSSION

In this study the usefulness of the ABR-threshold elicited by a click masked by high-pass-noise for predicting low-frequency hearing loss is investigated. In normal-hearing subjects the ABR-threshold amounted to 22 dB with a standard error of estimate of 3.5 dB (Conijn et al., 1990a). This, however, does not prove low-frequency-specificity in patients with a cochlear hearing loss.

For assessment of the low-frequency-specificity of the ABR-threshold elicited by the high-pass-noise-masked click, a difference in pure-tone hearing loss has to be present between the region of maximum correspondence of the unmasked click (2000 and 4000 Hz) (van der Drift et al., 1987; Gorga et al., 1985) on the one hand and the region of expected correspondence of the click masked with 1590 Hz high-pass masking-noise (1000 Hz) on the other hand. If this difference is not present, as for instance in subjects with a flat cochlear hearing loss, than no effect of frequency is to be expected in the relation between ABR-threshold and pure-tone threshold. In interpreting the correlation coefficients and the standard errors of estimate, the slope of the audiogram, the mean audiogram and the dynamic range of hearing losses are thus of critical importance. In table II can be seen that the mean audiogram represents a moderately sloping high-frequency hearing loss. However the mean *absolute* difference of the pure-tone audiogram between 1000 and '3000' Hz amounted to 27 dB which indicates that a sufficient difference between these frequencies has been made.

In our experiment 53 subjects were examined but in only 38 a useful ABR-threshold could be detected. As the maximum output level of the masking noise of our equipment is 100 dB nHL this means that, assuming a masker level which is 15 dB above click level, the maximum click level is about 85 dB nHL. This means that only hearing losses of about 75 dB or less at 1000 Hz can be detected. Even the noise level of 100 dB nHL was considered as disturbing by many patients especially those with hearing loss. Although patients were selected at having no greater hearing loss than 80 dB at 1000 Hz, 4 subjects could hardly tolerate the masking noise at a level of 90 dB and therefore their hearing loss was too large to be detected although in 3 the response quality was good enough to detect a response peak.
In 6 patients no ABR-threshold at all could be estimated and in 5 other patients the ABR-threshold was of a poor quality and was therefore not considered suitable for threshold comparison. The relatively low amount of useful ABR-thresholds can in part be attributed to the loudness of the masking noise which prevented many patients to sleep. As can be expected (see Table I) the response quality is dependent on the arousal state. Sleep or a very good relaxation is a prerequisite for a good low-frequency ABR-threshold. That the division in response quality classes is indeed clinically important can be conclude from the value for the correlation coefficients and the standard error of estimate for the different response qualities. If not only good and moderate quality ABR-thresholds are taken into account (as in Table III) but also ABR-thresholds with a bad response quality (N=43) then the correlation coefficient and standard error of estimate are 0.78 and 10.6 respectively. If only the good quality responses are taken into account (N=21) than the values are 0.90 and 8.4 respectively. The use of sedation can probably overcome this problem but this makes this method less suitable for routine clinical testing.

If the 1590 Hz high-pass masking-noise, used in this study, masks only the high-frequency predominance of the unmasked click generated ABR than a good correlation and low standard error of estimate is expected between ABR-threshold and the 1000 Hz pure-tone threshold, but not between ABR-threshold and higher frequencies. In Table III can

be seen that the best correlation of 0.81 with the lowest standard error of estimate of 10.2 dB is found at 1000 Hz and the worst correlation and the worst standard error of estimate is found at the higher frequencies.
From the scattergrams (Figure 2) can be seen that a fairly uniform distribution of pure-tone hearing losses has been selected. In Figure 2b two separate groups of data points can be discerned: the high-frequency hearing loss group in which the hearing loss at '3000' Hz is underestimated and the low-frequency hearing loss group in which the hearing loss at '3000' Hz is overestimated. This is in contrast with figure 2 where the data for both the high- and the low-frequency hearing losses are spread around the regression line.
We therefore conclude that, in this study, high-pass masking-noise with a cut-off frequency of 1590 Hz and a slope of 135 dB/octave with a masking level chosen by the electrophysiologic method adequately suppressed the high-frequency (2000 and 4000 Hz) predominance of the click generated ABR-threshold regardless of the slope of the pure-tone hearing loss.

The standard error of estimate of 10.2 dB at 1000 Hz is in the same range as the standard error of estimate of the unmasked click evoked ABR-threshold of 10.9 dB at 3000 Hz (van der Drift et al., 1987). The high-pass-noise-masked click evoked ABR-threshold is, therefore, not only low-frequency-specific but can also be as accurate in predicting the pure-tone hearing loss at 1000 Hz as the unmasked click evoked ABR-threshold is at '3000' Hz. The standard error seems high but is a result of both the inaccuracies of the pure-tone threshold and the ABR-threshold and of some other unknown factors which causes the less than perfect linkage between ABR-threshold and pure-tone threshold. These unknown factors are probably related to the fact that the ABR-threshold and the pure-tone threshold are basically different (van der Drift et al., 1987). The former being an electrophysiologic method, assessing the auditory system upto the brainstem and the latter a psychophysical method assessing the entire auditory system.

The mean difference between the ABR-threshold and the pure-tone threshold at 1000 Hz amounted to 16.4 dB (Table III). It is less than the value of 22 dB found in normal-hearing subjects (Conijn et al., 1990a). This means that the constant difference between PTT and ABR-threshold of 20-25 dB in normal-hearing subjects is diminishing to 10-15 dB for subjects with about 70 dB cochlear hearing loss. This phenomenon is also reflected by the slope of the regression line which is above 1. The probably cause is loss of temporal integration (Gorga and Worthington, 1983; Gorga et al, 1984) or an abnormal loudness growth (recruitment).

In the introduction we hypothesized that *low-pass* masking-noise was not necessary to restrict the click stimulus to the 1000 Hz region. Our results, that the correlation coefficient and standard error of estimate of the ABR-threshold with the PTT are much better for '1500' and 1000 Hz than for 500 Hz (Table III), supports this hypothesis at least at ABR-threshold level.

The possibility of splatter of the *high-pass* masking-noise in the 1000 Hz region at ABR-threshold level is unlikely on the basis of our results. The correlation and standard error of estimate at '1500' Hz is almost as good as at 1000 Hz (Table III) and this is not likely to occur when the masking noise would extend much beyond the 1590 Hz of the cut-off frequency. That the correlation and standard error of estimate of '1500' Hz are almost as good as those at 1000 Hz, indicates that the region in which the response is elicited is probably between 1000 and '1500' Hz. This is not at all surprising with a masking noise with a cut-off frequency of 1590 Hz and a filter slope of 135 dB/octave. In subjects with large cochlear hearing losses, some splatter is perhaps possible at ABR-threshold level because the response quality seems to deteriorate at high ABR-threshold levels. This can be due to the fact that in cochlear hearing loss the frequency-selectivity can be diminished and therefore more splatter from the noise masker can occur (Evans and Elberling, 1982). But this can also be due to the fact that the high levels of masking noise prevented many subjects to sleep which also causes a deterioration of the response quality.

During the experiment it was noted that the *suprathreshold* response peaks were often difficult to identify in patients with large cochlear hearing losses. In Figure 1b at the highest stimulus level (77 dB), which is only 15 dB above ABR-threshold level, almost no response peak can be seen while in a subject with normal hearing (Figure 1a) at the highest stimulus level, which is 50 dB above ABR-threshold, still a response peak can be seen although the amplitude is less than at lower stimulus levels. This difference between normal hearing subjects and subjects with large cochlear hearing losses can perhaps be attributed to loss of frequency-selectivity by which at suprathreshold levels the masking noise spreads more easily to lower frequency regions. The difficult identification of the suprathreshold responses in subjects with large cochlear hearing losses is a drawback of this masking method because the high amplitude suprathreshold responses are used to identify the major response peak and then follow it down to the ABR-threshold.

Although the 1590 Hz high-pass-noise-masked click, used in this study, is a reliable and accurate method for predicting the hearing loss at 1000 Hz the necessary masking noise makes it less suitable for routine clinical testing because of high loudness masking levels and the necessary electrophysiologic masking method which is time consuming because of the necessary adjustment of the masker level for each ear. Perhaps the recent introduction of brief tonal stimuli with special envelopes (Gorga et al., 1988; Gorga and Thornton, 1989; Conijn et al., 1990b) can provide a stimulus which is sufficiently frequency-specific and thus renders the use of masking noise superfluous for a reliable and accurate prediction of 1000 Hz pure-tone hearing loss.

CONCLUSIONS:

1. The ABR-threshold evoked by a click masked with high-pass masking-noise with a cut-off frequency of 1590 Hz and an electrophysiologically determined masker level can be a reliable and accurate tool to predict the pure-tone hearing threshold at 1000 Hz regardless of the slope of the pure-tone audiogram.
2. Low-pass masking-noise is not necessary to restrict the stimulus to the 1000 Hz region.
3. The downward spread of the high-pass masking-noise is probably minimal at ABR-threshold level.
4. The difficult identification of the suprathreshold responses in subjects with large cochlear hearing losses is a drawback of this masking method because the high amplitude suprathreshold responses are used to identify the major response peak and then follow it down to the ABR-threshold.
5. The necessary masking noise makes this method less suitable for routine clinical testing: because of high loudness masking levels, which decrease the dynamic range and decreases response quality by preventing the subjects to sleep and because of the necessary electrophysiologic masking method, a time consuming method because of the adjustment of the masker level for each ear.
6. Regarding point 4 and 5 of the conclusions the search for a method with no or less masking noise should continue.

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CHAPTER VI

FREQUENCY SPECIFIC ASPECTS OF THE AUDITORY BRAINSTEM RESPONSE THRESHOLD ELICITED BY 1000 HZ FILTERED CLICKS IN SUBJECTS WITH SLOPING COCHLEAR HEARING LOSSES

ABSTRACT

The frequency-specificity of the ABR-threshold evoked by a 1000 Hz filtered click was determined in subjects with sloping cochlear hearing losses, both high- and low-frequency in character. The results show that the ABR-threshold evoked by this stimulus is low-frequency-specific. The standard error in estimating the 1000 Hz pure-tone threshold is 10.4 dB, which equals that for estimating the 3000 Hz pure-tone threshold from the routinely used click evoked ABR-threshold (van der Drift et al., 1987). The ABR-threshold evoked by a 1000 Hz filtered click can therefore be regarded as an accurate tool to predict the pure-tone hearing loss at 1000 Hz. In comparison with the ABR-threshold evoked by a click masked with 1590 Hz high-pass-noise (Conijn et al., accepted for publication in Audiology), the ABR-threshold evoked by a 1000 Hz filtered click has a larger dynamic range, yields a larger number of useful responses and is less time-consuming. For clinical low-frequency-specific ABR-threshold assessment, the 1000 Hz filtered click is therefore preeminently useful.

RÉSUMÉ

La spécificité en fréquence du seuil des potentiels évoqués du tronc cérébral pour un clic filtré centré autour de 1 kHz est déterminé chez les patients présentant avec une surdité sensorielle et un audiogramme incliné positivement ou négativement. Les résultats montre que ce seuil est spécifique en fréquences bas. L'écart-type de la détermination du seuil d'audiogramme à 1 kHz par le seuil objectif est 10.4 dB. C'est égal à l'écart-type de la détermination du seuil d'audiogramme a 3 kHz par le seuil du potentiel évoqués du tronc cérébral par un clic non-masqué de routine (van der Drift et al., 1987). Donc le seuil objective spécifique en fréquences bas est qualifié pour détermination de la mesure de la surdité à 1 kHz. En comparaison du seuil du potentiel évoqués du tronc cérébral par un clic au fond d'un bruit masquant les fréquences au dessous de 1.59 kHz (Conijn et al., accepté par Audiology), le seuil pour le clic filtré a une étendue plus grande, fournit plus des réponses utilisables et prend moins de temps. Pour cettes raisons le clic filtré est le stimulus préférentielle pour la détermination du seuil spécifique en fréquences bas dans la clinique.

INTRODUCTION

The normal click evoked Auditory Brainstem Response (ABR) threshold corresponds with the higher frequency thresholds (2000-4000 Hz) in the pure-tone audiogram (van der Drift et al., 1987; Gorga et al., 1985; Coats and Martin, 1977). It is, however, also important to obtain information about hearing loss in the low-frequencies (500-1000 Hz) for various reasons: firstly, hearing loss usually starts and is most severe in the higher frequencies and therefore the click evoked ABR-threshold can overestimate the hearing loss in the lower frequencies. Secondly, hearing loss, restricted to the lower frequencies might go undetected with the click evoked ABR-threshold. This low-frequency hearing loss can, however, seriously jeopardize speech development. Furthermore, the fitting of a hearing aid can be done better if information about low-frequency hearing loss is available.

Two major approaches for obtaining low-frequency-specific ABR-thresholds can be distinguished: I. The use of masking noise and II. The use of a frequency-specific stimulus.
The first approach involves masking noise to isolate frequency-specific response area's in the cochlea (Eggermont, 1976). In our earlier reports a click masked with high-pass noise with a cut-off frequency of 1590 Hz was used as stimulus (Conijn et al., 1990a; Conijn et al., accepted for publication in Audiology). With this stimulus, a reliable ABR-threshold can be obtained in normal-hearing subjects (Conijn et al., 1990a). The same stimulus was also used in ABR-threshold assessment of subjects with both high- and low-frequency cochlear hearing loss (Conijn et al., accepted for publication in Audiology). In that study the relation between the ABR-threshold and the pure-tone threshold had its highest correlation (0.82) and its lowest standard error of estimate (10.2 dB) at 1000 Hz. This ABR-threshold assessment technique can therefore be regarded as low-frequency-specific. The technique has, however, several disadvantages which are due to the relatively high levels of masking noise necessary to adequately mask the high-frequency regions of the cochlea (Conijn et al., 199?c).
These disadvantages are:

1. Disturbing loudness of the masking noise, which causes restlessness and thus decreases response quality, especially in subjects with cochlear hearing loss.
2. Difficult identification of suprathreshold ABRs especially in subjects with cochlear hearing loss.
3. Decreased dynamic range in which hearing loss can be measured.
4. Time-consuming adjustment of the proper masker level.

Therefore an ABR-threshold assessment method with less or no masking noise is still much needed. Such a method is the second major approach for obtaining a low-frequency-specific ABR-threshold. This method uses a brief tonal stimulus for evoking the ABR. This tonal stimulus can have an electrical and acoustical narrow frequency spectrum. But as only a small part of the stimulus is effective in evoking the ABR (Kodera et al., 1983), the frequency-specificity inevitably diminishes because of the trade off between time and frequency (Gabor, 1947). Furthermore, because of the asymmetry of the travelling wave on the basilar membrane, a low-frequency stimulus can evoke responses from the higher frequency areas of the cochlea. The feasibility of such a low-frequency stimulus is, therefore, much disputed (for a review see Conijn et al., 1990b). At *suprathreshold* stimulus levels the low-frequency stimulus was proven not to be low-frequency-specific but to correspond to the 2000 and 4000 Hz pure-tone thresholds. However, low-frequency-specific ABR-*threshold* assessment is possible in normal-hearing subjects and in subjects with a flat cochlear hearing loss (Gorga et al., 1988, Conijn et al., 1990b), provided that: 1. a response filter with a low-cut-off frequency of less than 50 Hz is used, 2. the subject is relaxed and preferably sleeping, and 3. the stimulus has a rise-fall time of between 3 to 5 ms and no spectral side-lobes. From 20 dB above ABR-threshold level in normal hearing subjects and from 10 dB above ABR-threshold level in subjects with cochlear hearing loss, low-frequency-specificity diminishes, and the stimulus evokes responses from the higher frequency areas of the cochlea (Conijn et al., 1990b). Thus the dynamic region in which the low-frequency stimulus indeed evokes a low-frequency-specific response is small, and it remains to be seen whether these stimuli are clinically useful in subjects with sloping cochlear hearing losses, especially low-frequency in character.

This study was, therefore, undertaken to establish the frequency-specificity and the clinical feasibility of the ABR-threshold evoked by a 1000 Hz filtered click, in subjects with high- and low-frequency cochlear hearing loss.

METHODS

Subjects

Fifty hearing-impaired subjects were tested, one ear of each subject being examined. Their pure-tone thresholds (PTTs) were measured at 250, 500, 1000, 2000, 4000 and 8000 Hz. Only subjects with sloping cochlear hearing losses both high- and low-frequency in character and with normal tympanic membranes were included in this study. A hearing loss is defined as sloping if an absolute difference of 20 dB or more existed between the PTTs at 1000 and '3000' Hz (mean 2000 and 4000 Hz). From an earlier study (Conijn et al., 1990b) 5 subjects with a PTT better than 15 dB HL for 500 trough 4000 Hz were also included. This was done to increase the dynamic range of losses and to enable

comparison with other data. The subjects were instructed to lie down on a bed in an acoustically insulated chamber and to relax.
The arousal state of the subject was scored as sleep or no sleep in 35 of the 55 subjects. In all cases the probable cause of the cochlear hearing loss was scored.

Stimulation

The stimulus was generated by passing a click of 100 μs electrical duration through a bandpass filter with cut-off frequencies of 890 and 1120 Hz. The filter slopes were 135 dB/octave and the theoretical noise floor was 96 dB down (Kemo VBF/24). The repetition rate of the stimulus was 20 Hz and its polarity alternating. The stimulus was attenuated (Hewlett Packard 350 D) with 10 dB steps well above ABR-threshold and with 5 dB steps near ABR-threshold. The stimulus level is expressed in dB nHL. 0 dB nHl was equivalent to 24 dB peSPL as measured via a B&K 4153 artificial ear. The stimulus was presented monaurally to the subject via a TDH39 headphone with MX-41/AR ear-cushions. The acoustical stimulus and acoustical spectrum are presented in Figure 1.

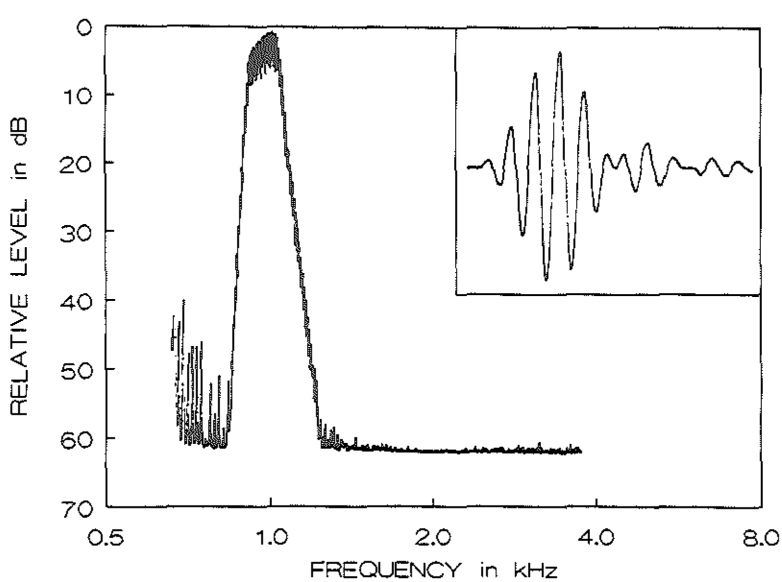

Figure 1
Spectrum and waveform (inset) of the 1000 Hz filtered click used in this study.

The stimulus envelope has an approximate rise-fall time of 3.5 ms and no plateau. The actual noise floor is more than 65 dB down (Figure 1).

ABR Recording

ABRs were recorded with chlorided silver cup electrodes. A two channel recording was made, the positive input was connected to the subject's vertex and the negative inputs to the mastoid of the stimulated ear for ipsi-lateral recording and to the non-stimulated ear for contra-lateral recording. A forehead electrode was used for the zero-lead. Inter-electrode impedances were always kept below 3 kΩ. The electrode signal was amplified 10^4 and band-pass filtered from 10 to 4000 Hz. The filter slopes were 24 dB/octave (Krohn-Hite 3322).
The electrode signal was averaged over 2048 sweeps that did not exceed ± 6.25 μV (artefact rejection). A time base of 15 ms was used.

ABR Identification

As our ABRs (Figures 2a and 2b) resemble those described by Suzuki et al (1981), we use their nomenclature and call the first positive peak P10 and the following negative trough N15.
At near-threshold stimulus levels the responses were repeatedly measured to test replicability. The responses were judged by the first and second author. The lowest stimulus level at which P10/N15 could be replicated was scored as ABR-threshold.
The latency measurements were determined for the positive peak (P10) or the edge of the negative slope (N15) (see Figure 2a and 2b for an example).
Response quality was also scored. The response quality was scored as "good" if P10 was clearly discernible and the baseline was more or less flat (as in Figure 2a). The response quality was scored as "moderate" if P10 was discernible but some noise was present in the response (as in Figure 2b) and as "bad" if P10 was hardly discernible.

Data processing

The mean pure-tone hearing loss at the frequencies 500 through 4000 Hz, the mean absolute difference between the pure-tone hearing loss at 1000 and '3000' Hz and the mean ABR-threshold are reported.

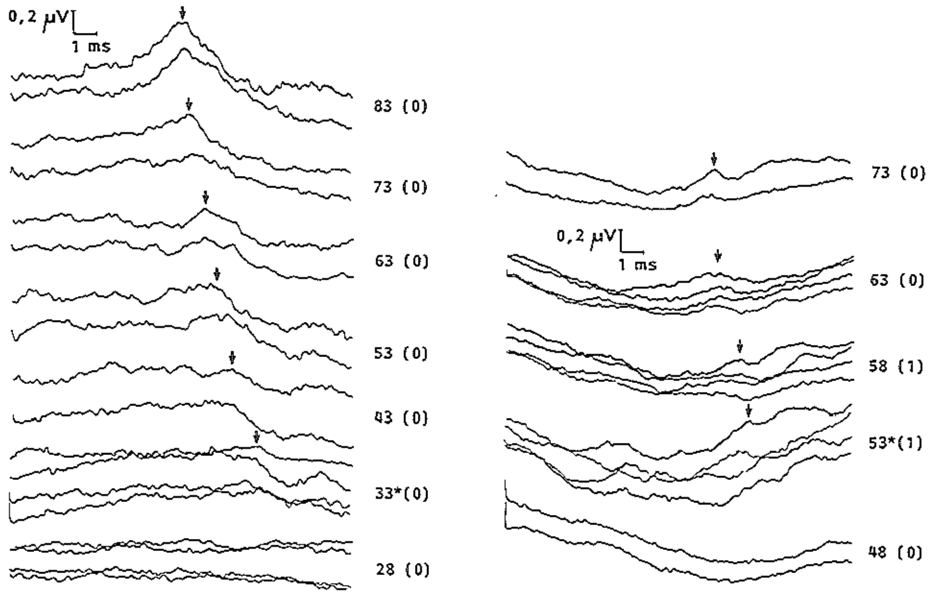

Figure 2a *Figure 2b*

Figure 2

Example of a series of auditory brainstem responses elicited by a 1000 Hz filtered click. Figure 2a of a subject with 15 dB and figure 2b of a subject with 40 dB cochlear hearing loss at 1000 Hz. The stimulation level is given in dB nHl with each response pair, the upper trace(s) show the ipsilateral recordings, the lower trace(s) the contralateral one(s). At and near ABR-threshold replications were made. The response quality score is indicated between brackets (0="good", 1="moderate"). The response peak is indicated with an arrow and the ABR-threshold is indicated with an asterisk.

The relation between ABR-threshold and the various frequencies of the pure-tone audiogram is reported with regard to the mean difference, standard deviation, correlation coefficient, slope of the regression line and standard error of estimate. For calculation of standard error of estimate and of the regression line both variables were considered as dependent because both were acquired with about equal measurement error. The PTTs at the frequencies '1500' and '3000' Hz are the calculated means of those for 1000 and 2000 and of those for 2000 and 4000 Hz, respectively. Statistical analysis was done with the SPSS-X computer program.

RESULTS

A total of 55 subjects was studied: 38 males and 17 females. Thirty seven with a high-frequency hearing loss (HFHL), 13 with a low-frequency hearing loss (LFHL) and 5 with no hearing loss (NHL). The subjects were between 11 and 88 years of age, mean age 53. In all 55 patients the quality of the responses was scored. In 35 patients the arousal state was scored. The relation between the quality of the ABR-threshold and the arousal state is shown in Table I.

Table I

Cross table of quality of the ABR-threshold against arousal state. The figures between brackets represent the number of subjects where in retrospect the stimulus level was not adequately lowered to the real ABR-threshold.

	AROUSAL STATE			
Response Quality	Sleep	No Sleep	Not Scored	Total
Good	14	3 (1)	15	32 (1)
Moderate	5	5 (3)	2	12 (3)
Bad		4	2 (1)	6 (1)
Total	19	12 (4)	19 (1)	50 (5)

In 5 subjects no reliable ABR-threshold could be scored because at the time of response judgment it appeared that the stimulus level had not been reduced to a level at which no ABR could be seen.

Unless specified otherwise the results which follow are derived from both "good" and "moderate" quality responses. This resulted in 13 subjects with a low-frequency hearing loss, 26 subjects with a high-frequency hearing loss and 5 subjects with no hearing loss. The cause of the hearing loss was mostly presbyacusis and noise induced hearing loss in the high-frequency hearing loss group and congenital and Meniere's disease in the low-frequency hearing loss group.

The mean, range and standard deviation of the pure-tone hearing loss, of the *absolute* difference between the 1000 and '3000' Hz PTTs and of the ABR-threshold are shown in Table II.

In Table III the statistical data describing the relations between the ABR-threshold and the PTTs at various frequencies are given.

Table II
Mean, range and standard deviation of the pure tone hearing loss at the various frequencies, of the absolute difference between 1000 and '3000' Hz (DIFF) and of the ABR-threshold (ABR-T). The figures for mean and range of the pure tone hearing losses are given in dB HL, the figures for the mean and range of the ABR-threshold are given in dB nHL, all other figures are given in dB.

	Pure-tone Frequency (Hz)							
	500	1000	'1500'	2000	'3000'	4000	DIFF	ABR-T
Mean	34	33	35	37	46	54	27	47
Range	0 - 95	-5 - 85	-5 - 73	-5 - 85	-3 - 98	0 - 120	-43 - 63	18 - 83
St.dev	23.8	22.3	19.8	23.4	26.7	32.6	28.2	17.5

Table III
Statistical data on the relation between the ABR-threshold and the pure-tone thresholds for the various frequencies. Mean difference between pure-tone threshold at that frequency and ABR-threshold; Standard deviation of this difference; Correlation coefficient; Slope of the regression line and Standard error of the estimate are given respectively.

	Pure-tone Frequency (Hz)					
	500	1000	'1500'	2000	'3000'	4000
Mean difference (dB)	12.4	13.9	11.6	9.3	1.4	-6.5
St. dev. of difference (dB)	12.6	11.7	13.4	21.9	27.6	35.1
Correlation coefficient	0.86	0.86	0.74	0.45	0.27	0.01
Slope of regression line	1.4	1.3	1.2	1.8	3.0	50.0
St. err. of estimate (dB)	10.9	10.4	12.5	18.4	21.5	23.8

In Figure 3a the scattergram of the ABR-threshold against the PTT at 1000 Hz is shown. The correlation coefficient is 0.86, the standard error of estimate is 10.4 dB and the slope of the regression line is 1.3. In Figure 3b the scattergram of the ABR-threshold with the pure-tone hearing loss at '3000' Hz is shown. Correlation coefficient is 0.27, the standard error of estimate is 21.5 dB and the slope of the regression line would be 3.0.

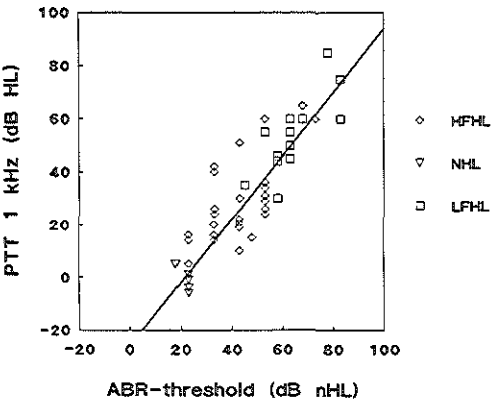

Figure 3a

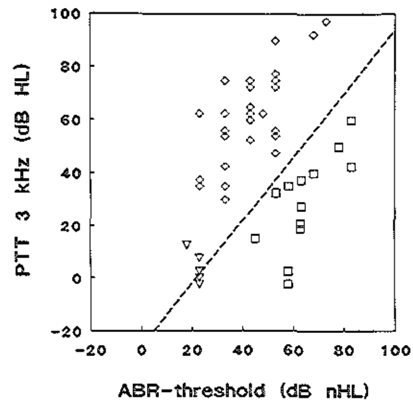

Figure 3b

Figure 3

Scattergrams of the ABR-threshold evoked by a 1000 Hz filtered click against the pure-tone threshold at 1000 Hz (Figure 3a) and against the pure-tone threshold at 3000 Hz (Figure 3b). Solid line represents the regression line (Figure 3a), the dotted line in Figure 3b represents the regression line for the 1000 Hz frequency of Figure 3a. Different symbols denote different types of hearing loss; HFHL: high–frequency hearing loss, NHL: no hearing loss, LFHL:low-frequency hearing loss.

DISCUSSION

Although low-frequency-specific ABR-threshold assessment is possible with the use of masking noise (Conijn et al., 1990a, Conijn et al., accepted for publication in Audiology), the use of this masking noise has several disadvantages discussed in the introduction. Therefore a low-frequency-specific stimulus without masking noise is still much needed. In normal hearing subjects and in subjects with flat cochlear hearing losses, a low-frequency-specific ABR-threshold can be obtained, with a low-frequency-specific tonal stimulus, provided there are no spectral side bands (Gorga et al., 1988; Gorga et al., 1989; Conijn et al., 1990b). In subjects with sloping cochlear hearing losses this remains still to be seen. Therefore this study was undertaken to assess the low-frequency-specificity of the ABR-threshold elicited by a 1000 Hz filtered click in subjects with sloping cochlear hearing losses. The selection of steep cochlear hearing losses is important because only these hearing losses can reveal frequency-specificity (Conijn et al., accepted for publication in Audiology). In table II it can be seen that the difference between the 1000 and '3000' Hz pure-tone thresholds is rather small (13 dB), this can be attributed to the fact that high- and low-frequency hearing losses balance out. The mean *absolute* difference between 1000 and '3000' Hz is, however, 27 dB (Table II, DIFF). Therefore the difference between 1000 and '3000' Hz is realistically large and should reveal differences, if any, between the relations of the ABR-threshold and PTT of these frequencies.

In Table I it can be seen that sleep improves the quality of the ABR-threshold. This is probably due to an improved S/N ratio (Conijn et al., 1990a). Apart from 5 subjects, in whom at the time of response judgement the ABR-threshold could not be estimated because the stimulus level appeared not to have been lowered to ABR-threshold level, a reliable ABR-threshold could be estimated in 44 of 50 subjects. In the remaining 6 subjects the quality of the ABR-recordings was too poor, in at least 4 cases due to restlessness.

If the 1000 Hz filtered click used in the present study is low-frequency-specific, a high correlation coefficient and a low standard error of estimate is to be expected between the ABR-threshold and the PTTs at low-frequencies and a low correlation coefficient and a high standard error of estimate with the PTT at high frequencies. In table III it can be seen that this is indeed the case: the correlation coefficient at 1000 Hz is 0.86 with a standard error of estimate of 10.4, whereas at '3000' Hz the correlation coefficient and standard error of estimate are 0.27 and 21.5, respectively. In the scattergrams (Figure 3a and 3b) it can be seen that a fairly uniform distribution of pure tone-hearing losses has been selected. In Figure 3b two separate groups of data points can be discerned: the high-frequency hearing loss group in which the hearing loss at '3000' Hz is underestimated and the low-frequency hearing loss group in which the hearing loss at '3000' Hz is overestimated. This is in contrast with figure 3a where the data for both the high- and the low-frequency hearing losses are evenly spread around the regression line. We therefore conclude that the 1000 Hz filtered click used in this study is able to elicit a low-frequency-specific ABR-threshold both in high- and low-frequency hearing loss.

The standard error of estimate of 10.4 dB at 1000 Hz is virtually equal to the standard error of estimate for the unmasked click-evoked ABR-threshold at 3000 Hz of 10.9 dB (van der Drift et al., 1987). The 1000 Hz filtered click-evoked ABR-threshold is, therefore, not only low-frequency-specific but can also be as accurate in predicting the pure-tone hearing loss at 1000 Hz as the unmasked click-evoked ABR-threshold is at 3000 Hz. The standard error seems high, but is a result of both the inaccuracies of the

PTT and the ABR-threshold and of some other unknown factors which cause the less than perfect linkage between ABR-threshold and PTT. These factors are probably related to the fact that basically different thresholds are involved (van der Drift et al., 1987).

The mean difference between the ABR-threshold and the PTT at 1000 Hz amounted to 13.9 dB (Table III). It is less than the value of 19 dB found in normal-hearing subjects (Conijn et al., 1990a). This means that the constant difference between PTT and ABR-threshold of 19 dB in normal-hearing subjects diminishes with increasing hearing loss. The difference is reduced to around 10 dB for subjects with about 70 dB cochlear hearing loss. This phenomenon is also reflected by the slope of the regression line which is above 1, in similarity to that reported for tonepips in notched noise (Stapells et al., 1990). The probable cause is loss of temporal integration (Gorga and Worthington, 1983) or abnormal loudness growth (recruitment).

It is generally believed that the ear's loss of sensitivity as a function of frequency, as shown by the audiogram, images the severity of damage of the cochlea as a function of place along the basilar membrane. But because of the asymmetry of the travelling wave, all low-frequency stimuli, if loud enough, can stimulate higher frequencies. In cases of LFHL it is, therefore, readily imaginable that the low-frequency threshold, be it pure-tone- or ABR-threshold, indicates a less severe damage of the more apical parts of the basilar membrane than really exists. It is known that in PTT testing, no differences between 1000 and 4000 Hz larger than 60 dB are found in LFHL. For the purpose of our own study we tried hard to find cases with LFHL but were not able to find a difference larger than 43 dB between the PTTs at 1000 and '3000' Hz. These results are also confirmed by an experimental study in chinchillas (Smith et al., 1987).
For the ABR-threshold evoked by the 1000 Hz filtered click, the maximum difference between the 1000 and 4000 Hz regions which can be assessed in LFHL can probably not exceed 40-50 dB (Conijn et al., 1990b). This maximum difference is, however, dependent on the frequency-selectivity of the cochlea. In subjects with cochlear hearing loss, and presumably diminished frequency-selectivity, the maximum difference is approximately 15 dB (Conijn et al., 1990b). A serious underestimation of LFHL is therefore to be expected.
In Figure 4, (Solid lines) hypothetical tuning curves are drawn for a subject with diminished frequency-selectivity (see Figure 7 Conijn et al,. 1990b) and a LFHL with a difference in sensitivity of 25 dB between 1000 and 4000 Hz. In this case, the low-

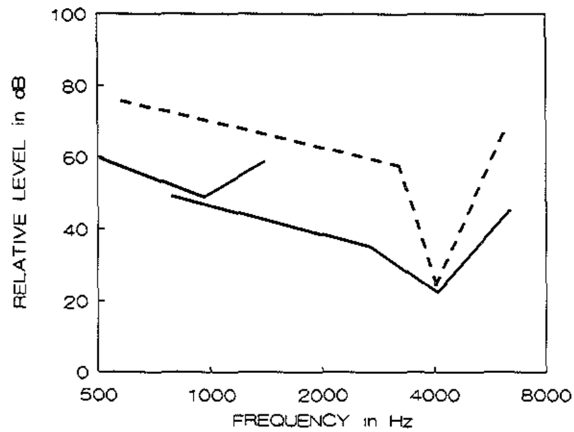

Figure 4
Hypothetical tuning curves for 1000 Hz and 4000 Hz. Solid lines represents a degraded frequency-selectivity, dotted lines a good frequency-selectivity.

frequency tail of the tuning curve of the 4000 Hz fibres is *below* the tip of the tuning curve of the 1000 Hz fibres. A 1000 Hz stimulus thus stimulates the high-frequency part of the cochlea and is thus not low-frequency-specific.
However, in our group of subjects with low-frequency hearing loss, we did not observe any gross underestimation. Although only 13 subjects were tested, it indicates that underestimating the LFHL, from the ABR-threshold evoked by a 1000 Hz filtered click, is not a frequent clinical problem.

Figure 5a *Figure 5b*

Figure 5
Correlation coefficients (Figure 5a) and standard errors of estimate (Figure 5b) of the ABR-threshold evoked by a 1000 Hz filtered click and evoked by a click masked with 1590 Hz high-pass-masking-noise across the various frequencies of the pure-tone audiogram.

A possible explanation is that the *frequency-selectivity* at these higher frequencies is not or less diminished, as is the sensitivity. This will lead to tuning curves as drawn with dotted lines in figure 4. Because of the preserved frequency-selectivity at the higher frequencies, the low frequency tail of the tuning curve of the 4000 Hz fibres is *above* the tip of the tuning curve of the 1000 Hz fibres and therefore low-frequency-specific ABR threshold assessment is possible.

In Figures 5a and 5b comparisons between the earlier described ABR-threshold evoked by a click masked with 1590 Hz high-pass-noise (Conijn et al., accepted for publication in Audiology) and the, in this study described, ABR-threshold evoked by a 1000 Hz filtered click are shown. As these studies were done with the same equipment and with virtually the same group of patients, a direct comparison is appropriate. The high-pass-noise-masked click evoked ABR-threshold tends to correspond somewhat more with the '1500' Hz PTT, but the differences are small, and both methods can be regarded as equally low-frequency-specific and equally accurate.

The methods differ, however, in the number of useful responses and the response quality. In table IV the response quality of both methods is given.

Response quality	Filtered click	Click/ Mask
Good	32	21
Moderate	12	17
Bad	6	5
No response		4
Total	50	47

Table IV
Response quality of the ABR-threshold evoked by a 1000 Hz filtered click (Filtered Click) and evoked by a click masked with 1590 Hz high-pass masking-noise (Click/Mask).

Because of the high level of masking noise, which is on average 15 dB above the click level, the dynamic range of stimulation is decreased. Therefore, in 4 cases with large hearing losses, no ABR-threshold could be estimated with the high-pass-noise-masked click, whereas with the 1000 Hz filtered click an ABR-threshold estimation was still possible. Because of the high loudness-levels of the masking noise, the subjects are much less relaxed and do not easily fall asleep, which deteriorates response quality. At suprathreshold stimulus levels the ABRs evoked by the high-pass-noise-masked click are less easily recognized especially in subjects with large cochlear hearing losses (Conijn et al., accepted for publication in Audiology). As these suprathreshold responses are used to identify the major response peak and then follow it down to the ABR-threshold, this peak identification problem is another drawback of the high-pass-noise-masked click method. A final drawback is the extra time needed for adjustment of the proper masker level.

The ABR-threshold evoked by a suitable brief tonal stimulus is, therefore, the method of choice for routine clinical low-frequency ABR-threshold assessment. Fortunately in many new ABR systems digitally-made brief tonal stimuli with, possibly, adequate envelopes, like the Blackman-Harris and Kaiser-Bessel windows, which have very low-level side-bands, are standard options

CONCLUSIONS:

1. The ABR-threshold evoked by a 1000 Hz filtered click can be a reliable and accurate tool to predict the pure-tone hearing loss at 1000 Hz, regardless of the slope of the pure-tone audiogram.
2. In comparison with the ABR-threshold evoked by a click masked with 1590 Hz high-pass masking-noise, the 1000 Hz filtered click evoked ABR-threshold is equally low-frequency-specific, equally accurate, and is superior in respect to the dynamic range of stimulation, response quality, time required and suprathreshold response recognition.
3. The present study thus indicates that the ABR-threshold elicited by a 1000 Hz filtered click is suitable for routine clinical assessment of low-frequency hearing loss, provided the subject is relaxed, and preferably sleeping, a low high-pass cut-off frequency of the response filter, a time-base of 15 ms or more, and artefact rejection with narrow limits are used.

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CHAPTER VII

COMPARISON BETWEEN THE FREQUENCY-SPECIFICITIES OF THE ABR-THRESHOLDS TO CLICKS WITH AND WITHOUT HIGH-PASS-MASKING-NOISE

ABSTRACT

In this study the frequency-specificity of the ABR-threshold to a click masked with 1590 Hz high-pass-masking-noise is compared with the frequency-specificity of the unmasked click evoked ABR-threshold. The ABR-threshold to the high-pass-noise-masked click stimulus is low-frequency-specific and corresponds with the 1000 Hz pure-tone threshold. Although the ABR-threshold to the unmasked click stimulus corresponds with the 3000 Hz pure-tone threshold, the frequency-specificity seems much less pronounced than that of the low-frequency-specific stimulus. This study shows, however, that this apparent lack of frequency-specificity can be attributed to the selection of pure-tone hearing losses. The ABR-threshold evoked by an unmasked click stimulus is, therefore, preeminently useful as a high-frequency point of a two point audiogram as proposed by Eggermont (1982). The possible reasons why the ABR-threshold evoked by a broadband stimulus as the unmasked click corresponds with the higher frequencies of the pure-tone audiogram, are discussed.

RESUME

La spécificité en fréquence du seuil des potentiels évoqués du tronc cérébral pour un clic masqué par un bruit aux fréquences au-dessus de 1590 Hz est comparé avec cette spécificité pour un clic non-masqué. Le seuil pour le stimulus premier est spécifique en fréquence basses et corresponds avec le seuil subjectif de l'audiogramme au fréquence de 1000 Hz. Le seuil pour le clic nonmasqué corresponds avec le seuil subjectif de l'audiogramme au fréquence de '3000' Hz. Mais la spécificité en fréquence paraits moins nettement défini. Il est montré que cet effet peut attribué aux differences dans la selection des audiogrammes des patients. Le seuil du potentiel du tronc cérébral pour un clic nonmasqué est des lors éminent utilisable comme un point aux frequences hautes dans un audiogramme objectif de deux points (Eggermont, 1982). Les raisons de cette spécificité bonne en fréquences hautes sont discuté.

INTRODUCTION

In a previous study (Conijn et al., accepted for publication in Audiology), the correlation between the various frequencies of the pure-tone audiogram and the ABR-threshold evoked by a click masked with 1590 Hz high-pass-noise was described: a strong correlation was found between ABR-threshold and the low-frequencies, and a very weak correlation with high frequencies. Regression analysis between the ABR-threshold and the pure-tone thresholds showed an optimum correlation (0.81) at 1000 Hz, with a

standard error of estimate of 10.8 dB. With the '3000' Hz pure-tone threshold these figure are 0.46 and 19.0 dB, respectively. The ABR-threshold to a 1590 Hz high-pass-noise-masked click can therefore be regarded as low-frequency-specific. This contrasts with the unmasked high-frequency-specific click evoked ABR-threshold (van der Drift et al., 1987; Gorga et al., 1985). In the study of Van der Drift, the best correlation of 0.93 and a lowest standard error of estimate of 11.1 dB are found between the ABR-threshold and the '3000' Hz pure-tone threshold. With the 1000 Hz pure-tone threshold, these figures are 0.82 and 17.1 dB respectively. The difference between correlation coefficients and standard error of estimate at 1000 Hz and '3000' Hz are thus much larger for the high-pass-noise-masked click than for the unmasked click evoked ABR-threshold. The frequency-specificity of the high-pass-noise-masked click evoked ABR-threshold, therefore, seems much more pronounced. As both the studies (Conijn et al., accepted for publication in Audiology and van der Drift et al., 1987) were done with virtually the same staff and equipment, differences can only be attributed either to the intrinsic properties of the stimulus and are therefore real, or can be attribute to the patient selection. When comparing correlation coefficients and standard errors of estimate the selection of pure-tone hearing losses is of crucial importance (Conijn et al., 1990). Perhaps the lack of frequency-specificity of the unmasked click evoked ABR-threshold can be attributed to the different selection of pure-tone hearing losses.
As we, following Eggermont (1982), propose a two point ABR-audiogram, it is of importance to know whether the click is as frequency-specific as the high-pass-noise-masked click. If not then a better high-frequency-specific stimulus has to be looked for. Therefore the original data of the unmasked click study of Van der Drift et al., 1987 were selected according to the criteria of the study on the 1590 Hz high-pass-noise-masked ABR-threshold (Conijn et al., accepted for publication in Audiology) to answer the question whether the unmasked click evoked ABR-threshold is indeed less frequency-specific or that this apparent lack of frequency-specificity can be attributed to the selection of pure-tone hearing losses.

METHODS

Three groups of subjects were included:

I. Subjects whose low-frequency-specific ABR-thresholds were assessed. The methods, material and subjects are described elsewhere in detail (Conijn et al., accepted for publication in Audiology). In summary ABR-threshold assessment was done to a click masked with 1590 Hz high-pass-noise. The masker level was chosen by electrophysiologic means. Forty nine subjects with steep cochlear hearing losses (absolute difference of 20 dB or more between the pure-tone thresholds at 1000 and '3000' Hz (mean 2000 and 4000 Hz) and four subjects with normal hearing were reported. Of each subject only one ear was tested. Because of the low S/N ratio of these low-frequency-specific ABRs, a reliable ABR-threshold could not be estimated in all cases. In total 26 ears with high-frequency hearing loss, 8 with low-frequency hearing loss and 4 with no hearing loss were included.

II. Subjects whose unmasked click evoked ABR-thresholds were assessed. These data and the method of acquisition were reported by Van der Drift et al., (1987). In summary routine ABR-threshold testing was done in patients referred by the ENT-clinic. Patients with conductive or retrocochlear hearing loss were excluded. Two hundred nine ears were reported from 138 subjects. So in contrast to the first group of subjects, these were not selected on the basis of the shape of the pure-tone audiogram.

III. Subjects from group II were selected on the basis of the audiogram shape, in order to obtain a group with pure-tone hearing losses resembling those in group I.

The following criteria were used:

1. Subjects with a high-frequency hearing loss, with a difference between the pure-tone thresholds at 1000 and '3000' Hz greater than 20 dB were included and no larger hearing loss than 100 dB at '3000' Hz, which amounted to 34 ears.
2. Subjects with a low-frequency hearing loss with a difference between the pure-tone thresholds at 1000 and '3000' Hz of less than or equal to 15 dB were included which amounted to 10 ears. This criterium is less strict than the 20 dB of the high-pass-noise-masked click study used in group I, because only 3 ears met the 20 dB criterium.
3. Subjects with normal-hearing (pure-tone thresholds better than 15 dB at 500 trough 4000 Hz) which amounted to 4 ears.

From these three groups the mean pure-tone hearing loss at the frequencies 500-4000 Hz, the mean absolute difference of the pure-tone hearing loss between 1000 and '3000' Hz, and the mean ABR-threshold are reported.

Data processing

For each group the relation between ABR-threshold and the various frequencies of the pure tone audiogram is reported, with regard to the mean difference, standard deviation, correlation coefficient, slope of the regression line and standard error of estimate.

For calculation of standard error of estimate and of the regression line both variables were considered as dependent, because both were acquired with about equal measurement error. The pure-tone thresholds at the frequencies '1500' and '3000' Hz are the calculated means of those for 1000 and 2000 Hz and of those for 2000 and 4000 Hz respectively.

Table I

Mean (dB nHL), range (dB nHL) and standard deviation (dB) of the pure-tone thresholds (top six main rows), of the absolute difference between 1000 and '3000' Hz (DIFF) and of the ABR-threshold, for each of the three groups of subjects: the 1590 Hz high-pass-noise-masked click evoked ABR-threshold [MASK (I)], the click evoked ABR-threshold for the total group II [CLICK, (II)] and for the selected sub-group [CLICK/SEL, (III)].

	GROUP	MEAN	RANGE	STD DEV
500	MASK (I)	30	0 - 65	19.5
	CLICK (II)	39	0 - 120	30.0
	CLICK/SEL (III)	23	0 - 90	22.3
1000	MASK (I)	30	0 - 65	18.7
	CLICK (II)	43	-10 - 130	30.9
	CLICK/SEL (III)	25	-10 - 80	21.5
'1500'	MASK (I)	34	0 - 73	17.8
	CLICK (II)	47	-3 - 128	30.5
	CLICK/SEL (III)	31	-3 - 73	19.3
2000	MASK (I)	37	0 - 85	22.9
	CLICK (II)	49	-5 - 125	31.8
	CLICK/SEL (III)	37	0 - 75	22.5
'3000'	MASK (I)	46	0 - 98	26.7
	CLICK (II)	56	0 - 120	30.7
	CLICK/SEL (III)	46	0 - 78	22.7
4000	MASK (I)	54	0 - 120	32.5
	CLICK (II)	60	-5 - 125	31.4
	CLICK/SEL (III)	55	-5 - 100	27.3
DIFF	MASK (I)	27	-43 - 63	26.3
	CLICK (II)	17	-30 - 65	17.8
	CLICK/SEL (III)	30	-30 - 65	25.6
ABR-T	MASK (I)	47	17 - 72	15.7
	CLICK (II)	55	5 - 110	28.1
	CLICK/SEL (III)	45	5 - 80	20.3

RESULTS

In Table I, the mean, range and standard deviation of the pure-tone hearing loss, of the *absolute* difference between 1000 and '3000' Hz and of the ABR-threshold are shown.

In Table II the statistical data, describing the relation between ABR-threshold and pure-tone audiogram are given for the three different patient groups: the high-pass-noise-masked click evoked ABR-threshold (group I), the unmasked click evoked ABR-threshold (group II) and the selection of the unmasked click evoked ABR-threshold (group III).

Table II

Statistical data describing the relation between the ABR-threshold and the pure-tone audiogram for each of the three groups of subjects: the 1590 Hz high-pass-noise-masked click evoked ABR-threshold [MASK (I)], the original click evoked ABR-threshold [CLICK (II)] and the selection of the click evoked ABR-threshold [CLICK/SEL (III)]: Mean difference between pure-tone threshold at that frequency and ABR-threshold (MEAN DIFF.); Standard deviation of this difference (STD. DEV.); Correlation coefficient (CORREL.); Slope of the regression line (SLOPE) and Standard error of the estimate (STD. ERR.) are given respectively.

	GROUP	MEAN DIFF.	STD. DEV.	CORREL.	SLOPE	STD. ERR.
500	MASK (I)	17.2	14.3	0.68	1.3	13.0
	CLICK (II)	15.4	22.8	0.68	1.11	20.9
	CLICK/SEL (III)	21.9	28.2	0.13	4.6	21.4
1000	MASK (I)	16.4	10.8	0.81	1.2	10.2
	CLICK (II)	11.1	18.2	0.82	1.13	17.1
	CLICK/SEL (III)	20.5	24.6	0.31	1.9	20.1
'1500'	MASK (I)	13.0	11.4	0.77	1.2	10.8
	CLICK (II)	8.1	14.0	0.89	1.18	12.7
	CLICK/SEL (III)	14.5	16.1	0.67	1.1	14.9
2000	MASK (I)	9.5	19.8	0.53	1.8	16.6
	CLICK (II)	5.0	13.3	0.91	1.14	12.6
	CLICK/SEL (III)	8.4	10.5	0.85	1.1	11.2
'3000'	MASK (I)	1.0	23.8	0.46	2.2	19.0
	CLICK (II)	-1.9	11.6	0.93	1.10	11.1
	CLICK/SEL (III)	-0.9	10.5	0.89	1.1	10.1
4000	MASK (I)	-8.0	29.9	0.23	4.4	21.4
	CLICK (II)	-6.5	14.1	0.89	1.12	13.4
	CLICK/SEL (III)	-10.0	17.3	0.70	1.4	15.2

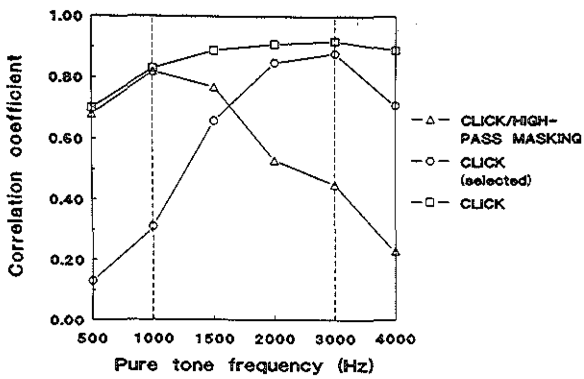


Figure 1a

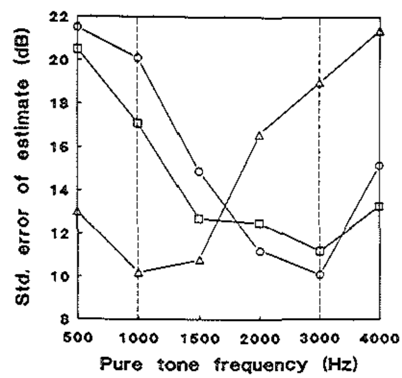


Figure 1b

Figure 1

Correlation coefficients (Figure 1a) and standard errors of estimate (Figure 1b) for the three different patient groups: the high-pass-noise-masked click evoked ABR-threshold (click/high-pass masking, group I), the unmasked click evoked ABR-threshold (click, group II) and the selection of the unmasked click evoked ABR-threshold (click selected, group III) across the various frequencies of the pure-tone audiogram.

In Figure 1a the correlation coefficients and in Figure 1b the standard errors of estimate are shown for each of the three groups across the various frequencies of the pure-tone audiogram.

In Figures 2a and 2c scattergrams of the ABR-threshold evoked by a click masked with 1590 Hz high-pass-noise (group I) with the pure-tone threshold at 1000 Hz (Figure 2a) and at '3000' Hz (Figure 2c) are shown. In Figure 2b and 2d scattergrams of the selection of the ABR-threshold evoked by an unmasked click (group III) with the pure-tone threshold at 1000 Hz and at '3000' Hz are shown.

DISCUSSION

The click evoked ABR-threshold corresponds with the '3000' Hz pure-tone threshold and can be regarded as frequency-specific for this frequency (van der Drift., 1987). But when comparing the correlation coefficients and standard errors of estimate of the click evoked ABR-threshold with those of the ABR-threshold to the 1590 Hz high-pass-noise-masked click (Conijn et al., accepted for publication in Audiology), the frequency-

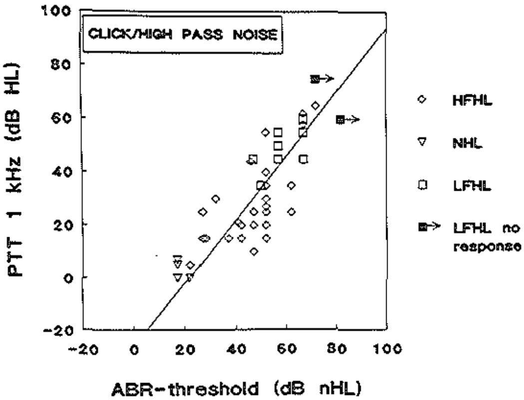
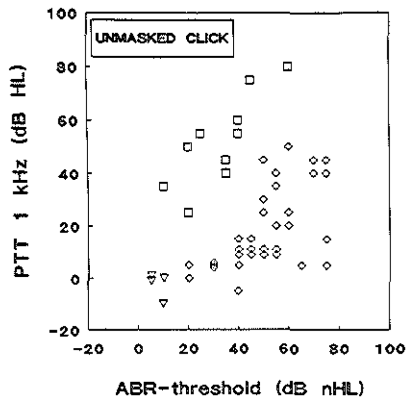


Figure 2a



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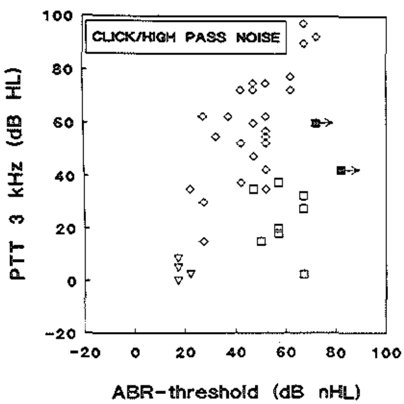


Figure 2c

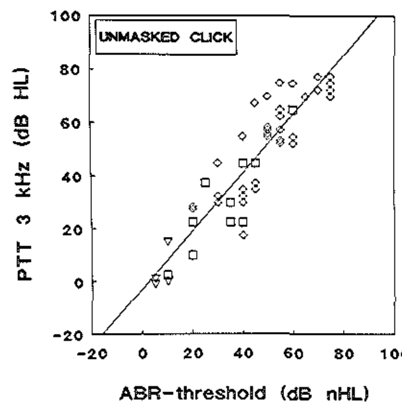


Figure 2d

Figure 2

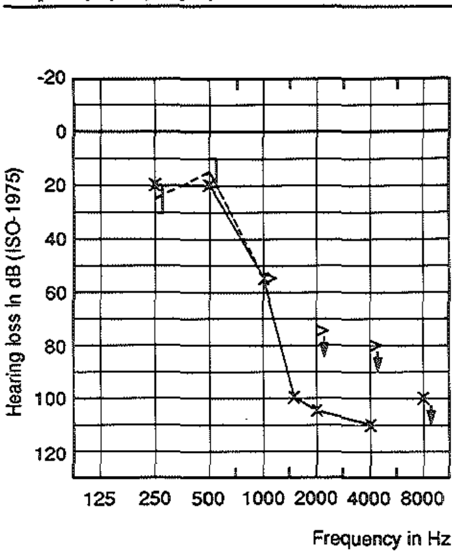
Scattergrams of the pure-tone threshold against the ABR-threshold at 1000 Hz (Figure 2a and 2b) and at '3000' Hz (Figure 2c and 2d). Panels a and c give results for the high-pass-noise-masked click evoked ABR-threshold (group I), panels b and d for the selection of the unmasked click evoked ABR-threshold (group III). Different symbols denote different types of hearing loss, HFHL: high-frequency hearing loss, NHL: no hearing loss, LFHL:low-frequency hearing loss, LFHL no response: highest stimulus level which was tolerated by the subject is given as ABR-threshold level although no response could be seen due to severe hearing loss. Solid lines represent the regression line.

specificity of the click evoked ABR-threshold seems much lower than that of the 1590 Hz high-pass-noise-masked click evoked ABR-threshold (Table II, Figures 1a and 1b). However, for a direct comparison of the results of these two studies the included pure-tone hearing losses have to be comparable. In table I it can be seen that the pure-tone hearing losses and especially the mean absolute difference between the pure-tone thresholds at 1000 and '3000' Hz (DIFF) of the high-pass-noise-masked click study (Conijn et al., accepted for publication in Audiology) are not resembling those of the Van der Drift study (van der Drift et al., 1987) (group II) because flat hearing losses were also included in this latter study. These flat pure-tone hearing losses can hamper the detection of frequency-specificity as represented by the correlation coefficients and standard errors of estimate (Conijn et al., 1990). Therefore a selection was made from the data of the unmasked click study of Van der Drift et al. (1987) according to the criteria for pure-tone hearing losses of the high-pass-noise-masked click study (Conijn et al., accepted for publication in Audiology). Table I shows that the pure-tone hearing losses and the shape of the audiogram of the selected group (group III) closely resembles those of the high-pass-noise-masked click group (group I). From the scattergrams (Figures 2a and 2d) it can be seen that the distribution of the pure-tone hearing losses and the numbers of high versus low-frequency hearing losses is also comparable. Therefore and because both studies were done with the same equipment and under comparable circumstances, a direct comparison between the data of group I and group III is valid.

Table I and figures 1a and 1b show that due to the selection based on the audiogram shape, the differences in correlation coefficients and standard errors of estimate between 1000 and '3000' Hz have dramatically increased. The magnitude of the frequency-specificity for the selection of the unmasked click study (group III) as reflected in these differences is now similar to that for the high-pass-noise-masked click study (group I). The scattergrams (Figure 2) show that both high- and low-frequency pure-tone hearing losses contribute to the good correlation and low standard error of estimate at '3000' Hz (Figure 2d) and the low correlation and high standard error of estimate at 1000 Hz (Figure 2b). In fact the data for the click evoked ABR-thresholds and the high-pass-noise-masked click evoked ABR-threshold seem to mirror each other for their respective frequencies: *low*-frequency hearing loss is underestimated by the click evoked ABR-threshold (Figure 2b), while the high-pass-noise-masked click evoked ABR-threshold underestimated the *high*-frequency hearing loss (Figure 2c).

We therefore conclude that the click evoked ABR-threshold is as frequency-specific at '3000' Hz as the 1590 Hz high-pass-noise-masked click evoked ABR threshold is at 1000 Hz. A two point audiogram with the click evoked ABR-threshold as high-frequency point thus is to be considered feasible.

It can be expected that the high-pass-noise-masked click generates a response in the apical region of the basilar membrane, because the high-pass-masking-noise according



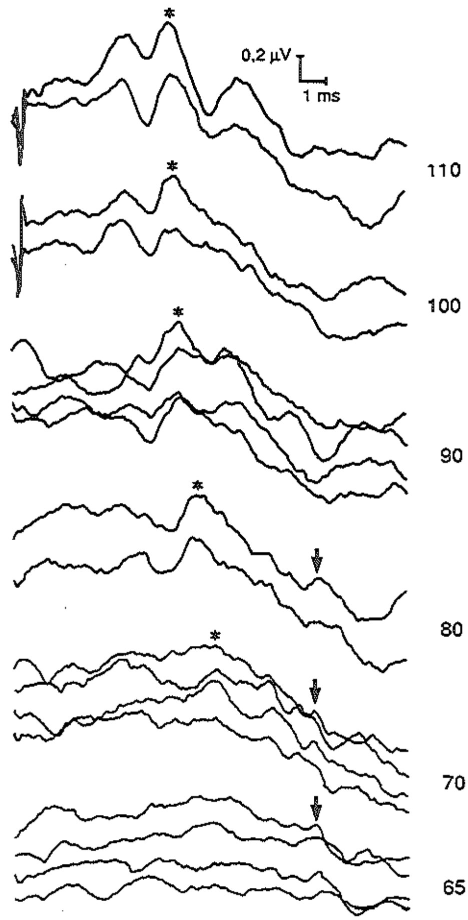


Figure 3
Example of a subject from whom a routine click evoked ABR-threshold was recorded from the left ear. Pure-tone audiogram is shown on the left, ABR-tracings on the right. The stimulus level is given in dB nHL beside each response pair, the upper response represents the ipsi-lateral and the lower the contra-lateral response. At the two lowest stimulus levels reproductions are shown. Peak V is marked with an asterisk, the ABR-threshold is 70 dB nHL (in this case of extreme high-frequency hearing loss the ABR-threshold underestimated the pure-tone hearing loss). Peak P10 is marked with an arrow and can be seen at a lower stimulus level than peak V, the ABR-threshold for peak P10 is not established.

to our data effectively masks the more basal areas without too much spread of masking noise in the apical region. It is surprising that the unmasked click is restricted to the more basal parts of the cochlea, especially so in high-frequency hearing loss (Figure 2d). In flat or no hearing losses, the predominance of the higher frequencies of the ABR is in part due to a cancelation of the low-frequency "apical" responses by the shorter latency high-frequency "basal" responses (Don and Eggermont, 1978), but in high-frequency hearing losses, as reported in this study there is no high-frequency "basal" response. From the fact that the high-pass-noise-masked click elicits a response in the 1000 Hz region it can be concluded that the click in itself has a sufficient amount of energy in this lower frequency range to elicit a response. So why does an unmasked click especially in case of a high-frequency hearing loss not elicit a response from the lower frequency regions? Perhaps an unmasked click can elicit a response in the lower frequency regions but this response remains undetected because of the longer latency and because of the different, rounded, form of the major response peak with its low amplitude. The ABR, originated in the low-frequency region, goes undetected when a time base of 10 ms and response filtering with a low-cut-off frequency of 100 Hz or higher is used (as is often the case in routine ABR-threshold testing). Weston and Manson (1985) reported a patient with a high-frequency hearing loss and good low-frequency hearing, who, when stimulated by an unmasked click showed a typical wave V response at stimulus levels above the pure-tone threshold in the 2000 to 4000 Hz range and a typical P10/N15 wave complex as the stimulus level decreased below the 2000-4000 Hz pure-tone threshold. Although not specifically mentioned in the original study of van der Drift et al. (1987), some patients with a high-frequency hearing loss demonstrated an unusual response peak with long latency (Figure 3). These response peaks could probably be observed because a standard time base of 15 ms and a response filtering of 10-3000 Hz was used and because some patients were relaxed enough to obtain the required good S/N ratio (Conijn et al., 1990). These response peaks were not regarded as waves V and therefore not taken into account in the ABR-threshold estimation. Possibly these response peaks were the low-frequency responses.

Another possibility is that the high-frequency part of the click, although not able to elicit a response in case of severe hearing loss in the high-frequency area, can still hamper the lower frequency part of the cochlear membrane, perhaps by a desynchronizing effect. Of course also a combination of these two hypotheses is possible. This study does not provide an answer to this question, but research in this field can help us to gain a better understanding of the unmasked click response.

CONCLUSIONS:

1. The click evoked ABR-threshold can be regarded as equally frequency-specific at '3000' Hz as the ABR-threshold evoked by a click masked with 1590 Hz high-pass-masking-noise is at 1000 Hz.
2. This high-frequency specificity at '3000' Hz even applies to subjects with steep high-frequency hearing losses.
3. The click stimulus is therefore pre-eminently useful for obtaining the high-frequency threshold point of a two point ABR-audiogram.

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Chapter VIII

Summary and Concluding Remarks

Introduction

Brainstem Electric Response Audiometry (BERA) is a method to visualize some of the electric activity generated in the auditory nerve and the brainstem during the processing of sound. The amplitude of the Auditory Brainstem Response (ABR) is very small (0.05-0.5 μV). The potentials originated by muscles and cortex cerebri, simultaneously recorded by the electrodes, are much stronger (5-500 μV). Isolation of the ABR from interfering or artifactual potentials is not a simple procedure. It is still a major problem to produce sufficient quality of response in BERA.

With BERA a threshold (Auditory Brainstem Response threshold) can be determined by attenuating the stimulus until no more ABR is identified. The commonly used stimulus is a click. The Auditory Brainstem Response threshold (ABR-threshold) to clicks was demonstrated to be a reliable indicator for hearing loss in the higher frequencies (2000/4000 Hz) (van der Drift et al., 1987, 1988a, 1988b).

Frequency-specificity is defined as the quality of the ABR-threshold to correspond with the pure-tone threshold in a specific limited pure-tone frequency band, without a similar correspondence to the threshold for frequencies outside this band. Therefore, frequency-specificity cannot be analyzed in subjects with normal hearing or in patients with a flat cochlear hearing loss (i.e. an equal amount of hearing loss for all pure-tone frequencies). Proof of frequency-specificity at ABR-threshold level should be found in a group of patients with low- or high-frequency pure-tone hearing losses. The frequency-specificity of the ABR-threshold to clicks was studied by van der Drift et al (1987) without selecting on the shape of the audiogram. To quantify the correspondence, linear regression analysis between the ABR-threshold and the pure-tone threshold for various frequencies was used. The correlation coefficients and standard error of estimate were found to be 0.93 and 11.1 dB for 3000 Hz and 0.82 and 17.1 dB for 1000 Hz respectively. The linkage of the ABR-threshold with the pure-tone threshold is much stronger for 3000 Hz than for 1000 Hz. The ABR-threshold to clicks can thus be regarded as specific for high frequencies, and is at present a standard clinical estimator for expected high-frequency hearing loss.

An important improvement of diagnostic possibilities in hearing loss can be gained by combining information by BERA about the hearing threshold for high- *and* low-frequencies -a "two point audiogram"- (Eggermont, 1982).

The aim of this study was to explore the possibilities to make such a two-point ABR-audiogram. After a review of literature, two methods were considered to be suitable for obtaining a low-frequency-specific ABR.
In the first place, the low-frequency specificity of the click stimulus masked with high-pass noise (Chapters III and V) and subsequently, the low-frequency specificity of the brief tonal stimulus (Chapter IV and V) was studied. Finally, the high-frequency-specificity of the standard click-evoked ABR-threshold was reevaluated, as both points of a two point ABR-audiogram should preferably have the same degree of frequency specificity.

Centre frequency for measuring the low-frequency ABR-threshold.

In this field of research "low-frequency" usual means 500 or 1000 Hz. ABR-thresholds to stimuli with a centre frequency of 500 Hz were previously reported for normal hearing subjects (Gorga et al., 1988; Don et al., 1979). The results were inconstant and the ABR-thresholds appeared to be higher than for 1000 Hz stimuli. In some reports only binaural ABR-thresholds were reported (van Zanten and Brocaar, 1984). The binaural ABR-threshold was demonstrated to be 5.5 dB better than the monaural ABR-threshold (Chapter III). Binaural ABR-threshold testing is obviously impractical, given the high prevalence of asymmetric hearing loss.
In a pilot study (Chapter II) the ABR-thresholds to stimuli with centre-frequencies of 500 Hz and 1000 Hz were compared. It was demonstrated that the ABR-threshold to stimuli with a centre-frequency of 500 Hz was very difficult to identify and always worse than for stimuli with a centre-frequency of 1000 Hz. It was concluded that a centre-frequency of 1000 Hz gives a better chance for clinically obtaining a reliable low-frequency-specific ABR-threshold in subjects with cochlear hearing loss.
Accordingly, the stimuli selected for this study were: 1. a click stimulus masked with a 1590 Hz high-pass noise, 2. a 1000 Hz filtered click as a brief tonal stimulus.

Prerequisites for low-frequency-specific ABR-threshold assessment

The ABR-peaks obtained by both methods appeared to be low in amplitude and of a rounded shape and at long latencies (more than 10 ms), as compared with the common click evoked ABRs. The rounded shape suggests a more low-frequency character of the response than the click evoked ABR. Therefore, a response filter setting with a low cut-off frequency below 50 Hz was needed (Stapells and Picton, 1981). This low cut-off frequency causes an increase in muscle artifacts during ABR-recording. This combination of low-amplitude response peaks and strong artifacts result in a very unfavourable signal to noise ratio and renders the identification of the low-frequency-specific ABR difficult. Artefact rejection, with narrow pass limits of $\pm$ 6.25 μV, was obligate to improve the signal to noise ratio. To prevent rejection of an unacceptably high proportion of sweeps, the patients had to be relaxed. It was shown in Chapter III that relaxation or sleep is a prerequisite for getting a response quality enabling low-frequency specific ABR-threshold assessment.

The ABR to a click masked with 1590 Hz high-pass noise

As reported in chapters III and V, ABRs evoked by a click masked with 1590 Hz high-pass noise could be obtained in normal hearing subjects. The ABR-threshold had a mean value of 22 dB nHL, with a standard error of the mean of 1.8 dB. At ABR-threshold level the mean latency of the major response peak amounted to 11.0 ms. This is approximately 3 ms longer than found for unmasked clicks. In view of the tonotopical arrangement in the cochlea, the long latency in normal hearing suggests a low-frequency origin of the response peaks. But it does not prove frequency-specificity in subjects with cochlear hearing loss.

To quantify the frequency-specificity of the ABR-threshold evoked by a click masked with 1590 Hz high-pass noise, patients were selected with either high- or low-frequency hearing loss. The ABR-threshold, elicited by a click masked with 1590 Hz high-pass noise, was correlated with the pure-tone loss at various frequencies. The degree of frequency-specificity was determined by linear regression analysis between the ABR-threshold and the pure-tone thresholds. The ABR-threshold was demonstrated to have a maximum correspondence with the 1000 Hz pure-tone threshold, with a correlation coefficient of 0.81, and a standard error of estimate of 10.2 dB. This correspondence is clearly better than the correspondence at the higher frequencies: at 3000 Hz the correlation coefficient and standard error of estimate are 0.46 and 19.0 dB respectively. It is concluded that the ABR-threshold elicited by a click masked with 1590 Hz high-pass noise can be regarded as an accurate tool to predict the pure-tone hearing loss at 1000 Hz, irrespective of the slope of the pure-tone hearing loss.

The ABR to a 1000 Hz filtered click

In chapters IV and VI a study of the other major approach for obtaining low-frequency-specific ABRs, the use of brief tonal stimuli, is reported.
In the literature, different opinions are reported about the low-frequency specificity of the ABR to a brief tonal stimulus. We hypothesized that frequency-specificity exists only at or near ABR-threshold level, and not at higher stimulus levels. Consequently, the frequency-specificity of the 1000 Hz filtered click was studied as a function of stimulus level: the latency of the major response peak (P10) of the ABR elicited by a 1000 Hz filtered click was compared with the latency of P10 elicited by the same stimulus *masked* with 1590 Hz high-pass noise. It was concluded that the 1000 Hz filtered click elicited low-frequency specific responses *at and near ABR-threshold level* in normal-hearing subjects, and in patients with a flat cochlear hearing loss. Frequency-specificity is degrading at 15 dB or more above ABR-threshold level in normal-hearing subjects, and at 5 dB or more in case of a flat cochlear hearing loss (Chapter IV). So, this margin is very narrow; which explains for the greater part the controversy on the frequency-specificity of brief tonal stimuli. Adversaries (Beattie and Boyd, 1985; Laukli and Mair, 1986) mostly used high suprathreshold stimulus levels, whereas advocates (Kobayashi et al., 1985; Kodera et al., 1977) reported studies near the ABR-threshold.

To quantify the frequency-specificity of the ABR-threshold evoked by a 1000 Hz filtered click, an experiment was done (Chapter VI) similar to that for the 1590 Hz high-pass-noise-masked click (Chapter V). In patients with either high- or low-frequency hearing loss, the ABR-threshold to a 1000 Hz filtered click was correlated with the pure-tone loss at various frequencies. Maximum correspondence was found with the 1000 Hz pure-tone threshold, with a correlation coefficient of 0.86, and a standard error of estimate of 10.4, whereas at 3000 Hz these figures were 0.27 and 21.5 dB respectively. The ABR-threshold evoked by a 1000 Hz filtered click can, therefore, be regarded as low-frequency-specific. The results showed that this low-frequency-specificity is independent of the slope of the pure-tone audiogram.
On theoretical grounds (Chapter IV) underestimation of the pure-tone loss at 1000 Hz might be expected in cases of low-frequency hearing loss combined with a loss of frequency selectivity. In our material, serious underestimation was not found. So, we conclude that this theoretical barrier to clinical application is not important.

Comparison of the clinical feasibility of both methods

The ABR-threshold to a 1000 Hz filtered click and the ABR-threshold evoked by a click masked with 1590 Hz high-pass noise are equally low-frequency-specific and accurate (Chapter VI). But, the latter method is less suitable for routine clinical testing because of the loud masking noise. Disadvantages due to the masking noise are: limited dynamic range of stimulation level, decreased response quality and time consuming adjustment of the masker level.
The 1000 Hz filtered click is the stimulus of choice in low-frequency-specific ABR-threshold assessment and can serve as a low-frequency point in the two point ABR-audiogram.

High-frequency-specificity of the standard click evoked ABR-threshold

The routinely measured click evoked ABR-threshold is proposed to serve as high-frequency point in a two point ABR-audiogram. Of course both points should preferably have the same degree of frequency-specificity. This means that the ABR-threshold to clicks must correspond as good with the 3000 Hz pure-tone threshold as the low-frequency ABR-threshold with the 1000 Hz pure-tone threshold. In addition, the ABR-threshold to clicks should correspond as poorly with the 1000 Hz pure-tone threshold, as the low-frequency ABR-threshold with the 3000 Hz pure-tone threshold.

The figures quantifying these correspondences, reported by Van de Drift et al (1987) and reported in this study (Chapters V and VI), suggested a difference in degree of frequency-specificity for the two points. In Chapter VII this difference was reconsidered. It was concluded that the difference is non-existing, as after application of the same criteria for patient selection, the same degree of frequency-specificity was found for the high-frequency point as we reported for the low-frequency point. The routinely tested ABR-threshold to clicks is, therefore, in our opinion suitable as high-frequency point in a two point ABR-audiogram.

FINAL CONCLUSIONS

I. Low-frequency-specific ABR-threshold assessment is possible with both a click stimulus masked with 1590 Hz high-pass noise and a brief tonal stimulus of 1000 Hz. The frequency-specificity of both methods is similar. Conditions to be fulfilled are an adequate response filter setting with a low-cut-off frequency below 50 Hz, a preferably sleeping subject, artefact rejection with narrow limits and a long time base of 15 ms.

II. Although on theoretical grounds underestimation of low-frequency-hearing loss with the brief tonal stimulus method can not entirely be excluded, underestimation was not found in our study.

III. The frequency-specificity of the ABR to the brief tonal stimulus is rapidly degrading as the stimulus level increases above ABR-threshold level. This explains the controversy in literature. Many studies, which demonstrate a lack of low-frequency-specificity, applied stimulation only far above ABR-threshold level.

IV. The 1000 Hz brief tonal stimulus is the stimulus of choice for low-frequency-specific ABR-threshold assessment. Because of the absence of the masker noise, this stimulus has the following advantages: 1. better response quality, 2. higher dynamic range of stimulation, 3. more time-effective.

V. The normal click evoked ABR-threshold is as *high*-frequency-specific as the ABR-threshold evoked by a click masked with 1590 Hz high-pass noise or the 1000 Hz filtered click evoked ABR-threshold are *low*-frequency-specific.

VI. A combination of the ABR-threshold evoked by a 1000 Hz brief tonal stimulus as low-frequency point and the conventional click evoked ABR-threshold as high-frequency point gives a two-point ABR-audiogram. This means an important extension of diagnostic possibilities.

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CHAPTER IX

SAMENVATTING

Hersenstamaudiometrie (Brainstem Electric Response Audiometry) is een onderzoek methode waarbij elektrische potentiaal verschillen ten gevolge van de door geluid opgewekte elektrische stroompjes, in binnenoor, gehoorzenuw en hersenstam, met behulp van computerapparatuur gemeten kunnen worden.

Deze methode wordt voor twee doeleinden gebruikt:

1. Bepaling van de geleidingstijd in gehoorzenuw en hersenstam. De geleidingstijd is o.a. toegenomen bij druk op de gehoorzenuw of hersenstam, door een tumor bijvoorbeeld.
2. Objectieve gehoormeting, in het bijzonder de objectieve gehoordrempel bepaling. Door het aangeboden geluid zo zacht te maken totdat er geen elektrische activiteit meetbaar is kan de gehoordrempel worden bepaald. Het voordeel van deze objectieve methode, boven de gangbare subjectieve audiometrie, is dat de medewerking van de patiënt niet is vereist, zelfs niet is gewenst. Ook bij slapende en bij in narcose gebrachte patiënten is deze methode toepasbaar. Deze methode is dan ook bij uitstek geschikt voor bepaling van gehoorverlies bij (kleine) kinderen. Het nadeel van deze methode is echter dat het gangbare geluid dat aangeboden word een zogenaamde klik is. Dit is een rechthoekig, kortdurend pulsje dat in principe alle frekwenties bevat. Uit eerder onderzoek blijkt dat een hersenstam-gehoordrempel correspondeert met de hoge tonen (3000 Hz) van het subjectieve toon audiogram. Met behulp van de hersenstam-gehoordrempel kan dus geen uitspraak gedaan worden over het voor de spraak zo belangrijke lage-tonen gebied rond 1000 Hz.

In dit proefschrift zijn verschillende methoden onderzocht om met behulp van de hersenstam-audiometrie toch een uitspraak te kunnen doen over gehoorverlies in het zo belangrijke laagfrekwente gebied. Deze laag-frekwente hersenstamdrempel kan dan fungeren als laag-frekwent punt in een tweepunts hersenstam-audiogram, zoals bepleit door Eggermont (1982). De als routine gemaakte hersenstamdrempel, die met een klik wordt opgewekt, kan dan dienen als hoog-frekwent punt.

Grosso modo kunnen 2 methoden voor laag-frekwente hersenstamdrempel bepaling worden onderscheiden:

1. Het gebruik van maskeerruis: samen met de klik of een toonpulsje wordt maskeerruis aangeboden, die als functie heeft om de hogere (3000 Hz) frekwenties weg te maskeren.
2. Het gebruik van een laag frekwente korte toonpuls.

Met laagfrekwent word over het algemeen de frekwenties 500 en 1000 Hz bedoeld. In de literatuur worden bij beide frekwenties hersenstam drempels bij normaal horenden beschreven. Bij sommige onderzoeken (van Zanten en Brocaar, 1984) zijn deze echter binauraal gemeten. Uit de literatuur en uit eigen onderzoek (Hoofdstuk II) blijkt dat de drempels bij 500 Hz niet altijd betrouwbaar gemeten kunnen worden; deze drempels liggen ook hoger dan bij 1000 Hz. Bovendien ligt de monaurale hersenstam drempel nog weer 5.5 dB hoger dan de binaurale (Hoofdstuk III). Dit maakt de drempel bij 500 Hz minder goed bruikbaar. De frekwentie van 1000 Hz lijkt daarom de beste kans te geven om een betrouwbare laagfrekwente hersenstam-drempel te bepalen bij patiënten met cochleaire gehoorverliezen.

De stimuli die uiteindelijk onderzocht werden zijn:

1. een klik stimulus gemaskeerd met maskeerruis met een hoog-afsnij-frekwentie van 1590 Hz
2. een 1000 Hz gefilterd klik

voor respectievelijk de maskeer-methode en de toon puls methode.

Indien aan een aantal voorwaarden wordt voldaan (o.a. ontspannen en liefst slapende patiënt, response filtering met laag-afsnijfrekwentie beneden 50 Hz, artefact onder-drukking met nauwe grenzen en een tijdbasis van 15 ms of meer) kan met beide methoden bij normaal-horenden een bruikbare hersenstam-respons worden gedetecteerd (Hoofdstuk III en IV). Vooral slaap tijdens het onderzoek is belangrijk omdat op deze manier een aantal stoorsignalen, afkomstig van spieren en hersenen, onderdrukt worden (Hoofdstuk III).

Het gebruik van een 1000 Hz toonpulsje is nogal omstreden omdat veel onderzoeken laten zien dat deze methode niet frekwentie specifiek is (de frekwentie van het aangeboden geluid, in dit geval 1000 Hz, is niet de frekwentie waarbij gemeten blijkt te worden). Deze onderzoeken zijn veelal gedaan met metingen ver boven de

gehoordrempel. Vlakbij de gehoordrempel is een toonpuls van 1000 Hz, zoals dat gebruikt is in deze studie, echter wel frekwentie-specifiek (Hoofdstuk IV).
Om de frekwentie-specificiteit bij patiënten te onderzoeken zijn patiënten geselecteerd wier gehoorverlies, zoals dat gemeten is volgens de conventionele subjectieve methode, niet vlak is. Indien er namelijk ook patiënten met vlakke verliezen zouden zijn geselecteerd dan zou dit een eventueel aanwezige frekwentiespecificiteit kunnen verhullen (Hoofdstuk IV).
De 1000 Hz toonpuls was bij patiënten met steile hoge- en lage tonen verliezen frekwentie-specifiek, met een hoogste correlatie coëfficiënt van 0.86 en een laagste standaard fout van 10.4 dB met de 1000 Hz toondrempel (Hoofdstuk VI). Alhoewel theoretisch de mogelijkheid van onderschatting van laag-frekwent gehoorverlies aanwezig is, is hiervan in de praktijk niets gebleken (Hoofdstuk VI).

De maskeer-methode was bij patiënten met steile hoge- en lage tonen verliezen eveneens frekwentie-specifiek, met een hoogste correlatie coëfficiënt van 0.81 en een laagste standaard fout van 10.2 dB met de 1000 Hz toondrempel.

Wat betreft frekwentie-specificiteit en nauwkeurigheid, waarmee uit de hersenstam-audiometrische drempel een schatting gemaakt kan worden over het gehoorverlies bij 1000 Hz, ontlopen de beide methoden elkaar dus niet veel. Echter, de bij de maskeer-methode benodigde ruis, die ongeveer 15 dB luider is dan de klik, beperkt de dynamiek van de stimulus, geeft verslechtering van de response kwaliteit en is tijdrovend vanwege het instellen. Dit maakt de maskeer-methode in vergelijking met de toonpuls methode minder goed bruikbaar voor routine-onderzoekingen (Hoofdstuk V en VI).
De 1000 Hz toonpuls is dan ook de methode van keuze voor routine bepaling van de laag-frekwente hersenstam-gehoordrempel.

De "gewone" hersenstam-gehoordrempel, die wordt opgewekt met behulp van een klik, correspondeert met de hogere frekwenties (3000 Hz) uit het conventionele toonaudiogram (van der Drift, 1988). Als zodanig zou deze, mits voldoende hoog-frekwentie-specifiek, kunnen fungeren als hoog-frekwent punt van een tweepunts hersenstam-audiogram. De frekwentie-specificiteit, zoals eerder beschreven door Van der Drift (1988), lijkt veel slechter dan bij de laag-frekwente metingen die in dit proefschrift beschreven zijn. Aangezien de klik een breedband stimulus is, hoeft dit geen verwondering te verwekken. Bij nadere beschouwing kan het verschil in frekwentie-specificiteit echter worden toegeschreven aan de ongelijke patiënten populaties. In het onderzoek van Van der Drift (1988) bevinden zich veel vlakke gehoorverliezen, die de frekwentie-specificiteit schijnbaar verminderen. Indien een selectie wordt gemaakt, zodanig dat beide patiënten populaties een vergelijkbaar gehoorverlies hebben, dan zijn de cijfers, voor wat betreft frekwentie-specificiteit en nauwkeurigheid, van vergelijkbare grootte.

CONCLUSIE

De routine hersenstam-gehoordrempel, die wordt opgewekt met behulp van een klik, kan uitstekend dienen als hoog-frekwent punt in het hersenstam-audiogram, terwijl de hersenstam-gehoordrempel, die wordt opgewekt met een 1000 Hz toonpuls, kan dienen als laag-frekwent punt om op deze manier het gehoorverlies in de zo belangrijke "spraakfrekwenties" te objectiveren. Op deze manier kan een tweepunts hersenstam-audiogram worden gemaakt zoals bepleit door Eggermont (1982) .

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CURRICULUM VITAE

De schrijver van dit proefschrift werd geboren op 26 juli 1956 te Rotterdam. In 1974 werd het eindexamen gymnasium aan het sint Franciscus College te Rotterdam behaald.

In verband met het uitloten voor de studie geneeskunde werd een aanvang gemaakt met de studie rechten aan de Erasmus Universiteit te Rotterdam, alwaar het kandidaatsexamen I behaald werd in 1976. In dat jaar werd hij ingeloot voor de studie geneeskunde, die eveneens gevolgd werd aan de Erasmus Universiteit te Rotterdam.

In 1978 maakte hij als student-assistent voor het eerst kennis met de afdeling Keel- Neus- en Oorheelkunde in het Academisch Ziekenhuis Rotterdam "Dijkzigt", toen nog onder leiding van Prof. Dr. E.H. Huizing. In 1981 is hij gedurende enkele maanden als wetenschappelijk medewerker verbonden geweest aan die zelfde afdeling en in het bijzonder aan het toenmalige binnenoorlaboratorium onder leiding van Dr. R.A. Tange.

In 1983 werd het artsexamen cum laude afgelegd waarna de schrijver werd opgeleid in de keel- neus- en oorheelkunde door Prof. Dr. C.D.A. Verwoerd en door Prof. Dr. P.C. de Jong in het Academisch Ziekenhuis Rotterdam, alwaar het onderzoek waarop dit proefschrift is gebaseerd in 1987 werd aangevangen.

In 1987 werd hij ingeschreven in het specialistenregister.

Van 1987 tot 1 april 1990 is hij werkzaam geweest als senior staflid in het Academisch Ziekenhuis Rotterdam met als bijzonder aandachtsgebied de kinder keel- neus- en oorheelkunde en de neuro-otologie. Vanaf 1 april 1990 is hij werkzaam als algemeen keel- neus- en oorarts in het ziekenhuis Lievensberg te Bergen op Zoom, eerst in associatie met H.C. Bisschop en vanaf 1 september 1990 in associatie met M.M.A. Mutsaers.

De schrijver is gehuwd en heeft één dochter, Eline.