Brainstem Response Audiometry in the determination of hearing loss

Hersenstamaudiometrie bij de bepaling van type en omvang van gehoorverlies

PROEFSCHRIFT

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Chapter I

General introduction

The earlier hearing disorders are diagnosed in infants and children the sooner treatment and revalidation can be organised. Consequently, determining the hearing at the youngest age possible is important to promote the development of language and communication. Brainstem response audiometry has the special advantage of being an objective method. Cooperation of the patient is not required so it can be applied even in the young children.
It is the aim of the present study to assess the reliability of this method by comparing with data obtained with pure tone audiometry. For the latter cooperation of the patient is essential. Therefore this type of investigation is not possible in children and has to be achieved in (cooperative) adults.

Definitions

In brainstem response audiometry an auditory stimulus is repeatedly presented to the patient through a headphone or in some cases through a bone conductor (fig.1). The stimulus most frequently used is a click. The click, used in this study, is a short acoustic stimulus (duration 100 microsec) with a wide frequency spectrum (chapter II, fig.1). The electrical activity of the brainstem in the 15 ms

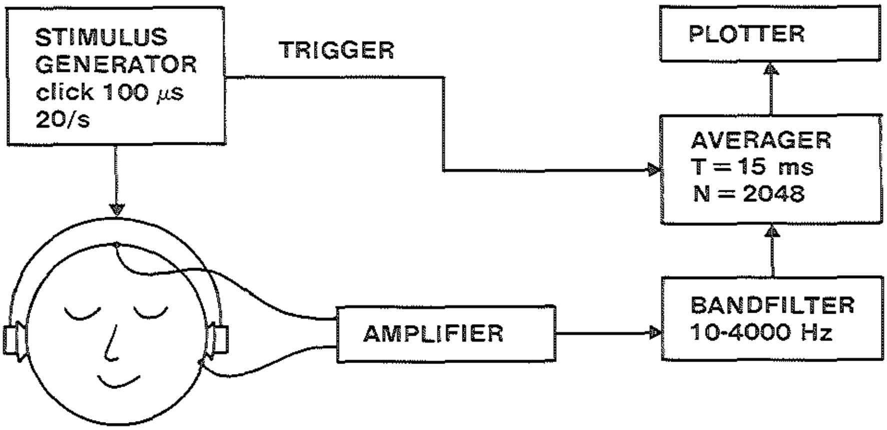

Fig. 1
Schematic representation of the measurement situation. Full description of the equipment and measurement procedure is given in chapter II.

following each click was measured using skin electrodes on the vertex of the head and on both mastoids. Averaging of the measured post-stimulus epoch results in a pattern of 5 peaks (peaks I-V). A typical example of such a response pattern is given in fig.2. The measurement is started at a high stimulation level (100 or 90 dBnHL) and. if the response shows peaks to be related to the response pattern. is successively repeated at lower levels. The lowest stimulation level at which a reproducible response can be detected is defined as the response threshold level. The abbreviation dBnHL stands for decibels normal Hearing Level: i.e. the level in decibels relative to the subjective click threshold level of the stimulus in subjects with normal hearing.

Another important feature of the auditory brainstem response is the latency of the various peaks. measured in ms from the onset of the stimulus. The latency of a peak can be plotted as a function of the stimulation level (chapter IV. fig.2). In the literature this curve is called the latency-intensity curve. In the present work we prefer the term latency-Level curve (l(L) curve). because it is incorrect to use the word intensity for a quantity. measured in decibels. The position of the l(L) curve is studied relative to a reference curve. based on data of subjects with normal hearing.

In brainstem response audiometry further the time interval between peak I and peak V is considered to be of clinical importance. A prolonged interval is regarded as an indication for retrocochlear pathology.

In the present study we focus on the response threshold and the position of the l(L) curve as instrument to determine the amount and type of peripheral (i.e. cochlear and conductive) hearing loss.

Introduction

The principle of brainstem response audiometry was described by Sohmer and Feinmesser in 1970. Its value in audiological practice. particularly for the detection of retrocochlear pathology. has been reported in the classical papers by Jewett et al.(1970. 1971). Thornton (1976). Selters and Brackmann (1977) and Terkildsen et al.(1978). In the years following the introduction of the method in our clinic in 1979 by Rodenburg and Van Olphen (Van Olphen (1983)). there has been a growing appreciation of its value for estimating the hearing level. together with a growing awareness of its limitations. Two aspects of brainstem response audiometry in particular were considered to need investigation: the reliability of this method for estimating the amount of hearing loss in various types of hearing loss and its value for distinguishing between types of hearing loss. As to the second issue it may be noted that auditory brainstem responses can be elicited using bone conducted stimuli. However. for practical reasons. to be discussed in the section

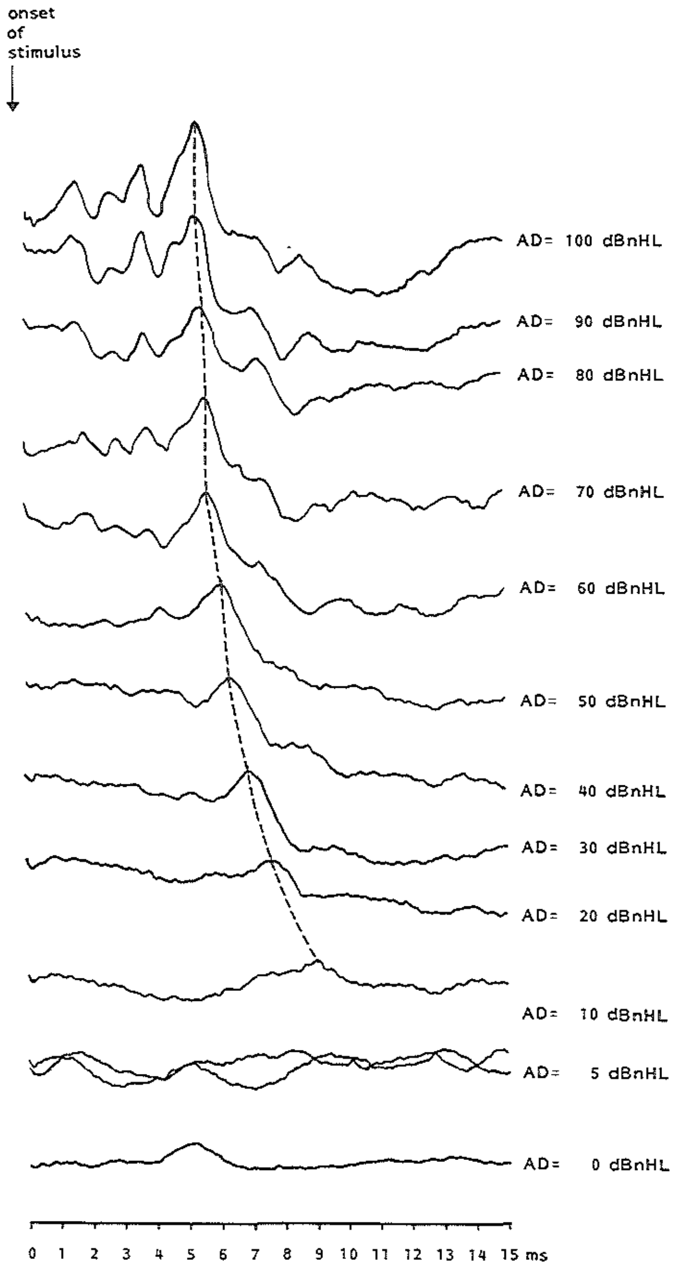

Fig. 2

Example of an auditory brainstem response pattern in normal hearing. The dotted line connects peak V at the different stimulation levels. The response threshold is found at 10 dBnHL. At 5 dBnHL stimulation level the two traces demonstrate the absence of a reproducible response. The time basis is given in milliseconds (ms). (AD means right ear).

on bone conduction in this chapter, we have not studied the feasibility of using bone conducted stimuli.

To test the reliability of brainstem response audiometry, it is necessary to compare the results obtained with some other method for measuring hearing capacity. The most suitable test for comparison is the subjective pure tone audiogram. However, this imposes restrictions on the conclusions of the investigation for the following reasons. First, pure tone audiometry and brainstem response audiometry are basically different methods for measuring different phenomena. The pure tone audiogram involves the entire auditory system from the external auditory canal to the cerebral cortex where the auditory sensation is perceived. In brainstem response audiometry, on the other hand, electrical phenomena are recorded that are generated up to the midbrain level. Another difference concerns the stimulus. In pure tone audiometry a continuous tone (duration >300 ms) of variable frequency is used. In brainstem response audiometry the stimulus is a click (duration 0.1 ms), the spectrum of which contains all audiogram frequencies. A priori therefore, one should not expect pure tone thresholds to be strongly correlated with the auditory brainstem response threshold. This problem is assessed in the discussion in chapter II. A further restriction on our investigation was a practical one: to obtain reliable tone audiograms for comparison with the brainstem response data, we were primarily confined to a test population of adult subjects, for tone audiometry is not possible in the infant population (0-3 year). However, it was demonstrated (Lary et al.(1985), Van Zanten et al.(1987)) that the brainstem response threshold at term age is about the same as found in adults. As for the latency of peak V, adults values were found in children from the age of three. In younger children the latency is prolonged (Despland and Galambos (1980)). For comparison with adult data correction factors were reported by Finitzo-Hieber et al.(1978).

Estimation of the amount of hearing loss

The first issue is the reliability of the auditory brainstem response threshold as an estimate of the hearing loss. Some consider that this response threshold gives a poor estimate of hearing loss. (Jerger and Mauldin (1978), Coats and Martin (1977) and Bellman et al.(1984)). Our own clinical experience did not confirm this. Therefore we assessed the brainstem response threshold and its relationship to the subjective pure tone audiogram in cochlear hearing loss (chapter II) and in conductive hearing loss (chapter VI).

Inaccuracy in measurement

As the position of the patient l(L) curve is used for quantitative diagnostic purposes, it is necessary to assess the inaccuracies involved in the measurement of this l(L) curve. Furthermore this knowledge is required to allow for certain statistical methods to be used for comparing brainstem response data with the pure tone audiogram. The measurement inaccuracies were studied in a test-retest experiment, the results of which are discussed in chapter III. We were interested in the accuracy of both the response threshold and the latencies of the various peaks in the response for all stimulation levels. The combination of these data is used to assess the amount and the type of hearing losses, as will be shown in the chapters IV and V.

Discrimination between different types of hearing loss

The reliability of the classification of cochlear, conductive and mixed hearing loss has consequences for the choice of treatment, being very different for the various conditions. Since most investigations are carried out in a critical period of speech development (0-4 years) it is important to know the reliability of the classification of hearing losses exclusively based on brainstem response data. This subject, not previously been discussed in literature, will be dealt with in chapters IV and V.

Discrimination between different types of hearing loss without response threshold available

In the "Sophia" Children's Hospital of the University Hospital Rotterdam, most patients are measured without sedation or general anaesthesia. In about 15% of the cases it is not possible to determine the response threshold because the patient is restless. Such restlessness causes a poor signal to noise ratio, resulting in the absence of the lower part of the l(L) curve and thus of the response threshold (being the lowest level point) too. This condition can be simulated by randomly truncating the lower parts of the l(L) curves in adult patients. In chapter VI we have shown the extent to which it is possible to determine the type of hearing loss, in a way similar to the method described in chapter V, when only the horizontal shift of the latency-Level curve and of its first derivative (see chapter IV for definition) can be used as parameters.

Bone conduction in brainstem response audiometry

The literature is unequivocal about the use of bone conduction in brainstem response audiometry. Hofmann and Flach (1981), Baschek et al.(1981) and Hooks and Weber (1984) found that the combination of the air-conducted and the bone-conducted brainstem response threshold is a reliable instrument for estimating the air-bone gap. Mauldin and Jerger (1979) advocated another parameter of the response to predict the air-bone gap in the tone audiogram in conductive hearing loss: they determined the air-bone gap by measuring the horizontal shift of the air-conducted I(L) curve relative to the bone-conducted I(L) curve. This method appears to be a reliable tool. Kavanagh and Beardsley (1979), however, reported problems such as low amplitudes, poor wave configuration and calibration difficulties. Consequently they found the bone-conducted brainstem response of limited value in differentiating conductive from cochlear hearing loss.

A special technique using bone-conducted stimuli in brainstem response audiometry is reported by Boezeman et al.(1983a.b, 1984, 1985) and Kapteyn et al.(1983): the cancellation method. Their combined use of air-conducted and bone-conducted stimuli with controlled phase and level differences was provided an accurate measurement of the air-bone gap, but it is rather cumbersome. Hicks (1980) demonstrated yet another way of using bone conduction in brainstem response audiometry and called it the "Derived Bone Conduction Threshold". In this method bone-conducted high-pass noise is used to mask the brainstem response just above the level of the response threshold. This method is comparable to the Sensory Acuity Level test in standard audiometry (Katz (1985)). The resulting prediction of the bone-conducted pure tone threshold, although only demonstrated in a few examples, gives the impression of being quite promising.

Till date the use of bone conduction in brainstem response audiometry leads to theoretical and practical difficulties. First the effect of dispersion of the pulse stimulus in the bone conductor itself and between the bone conductor and the inner ear is unknown. The derived bone conduction threshold gets round this obstacle by using the bone conductor as a masker instead of as a stimulator. The practical drawback of all methods of bone-conducted brainstem response audiometry is especially great in children, because of the large amount of extra time needed.

Though aware of the possible merits of bone-conducted stimuli in special cases, we decided to restrict ourselves in this study to investigating the value of air-conducted brainstem response audiometry.

Summarizing, the investigations reported in the present thesis were carried out to answer the following questions:

1. What is the relationship between the auditory brainstem response threshold and the pure tone audiogram in cochlear and conductive hearing loss?

2. How reliable is the classification of hearing losses based on linear discriminant analyses of data obtained by brainstem response audiometry?

References

Baschek V.. Steinert W.. Gelsenkirchen
Technik der Registrierung evozierter Hirnstamm- und Cortex-I-Potentiale in Luft- und Knochenleitung zur Bestimmung des Horvermogens
Laryng. Rhinol. 1981. 60: 139-146

Bellman S.. Barnard S.. Beagley H.A.
A nine year review of 841 children tested by transtympanic electrocochleography
J. Lar. Otol. 1984. 98: 1-9

Boezeman E.H.J.F.. Kapteyn T.S.. Visser S.L.. Snel A.M.
Effects of contralateral and ipsilateral masking of acoustic stimulation on the latencies of auditory evoked potentials from cochlea and brainstem
Electroenc. Clin. Neurophys. 1983a. 55: 710-713

Boezeman E.H.J.F.. Kapteyn T.S.. Visser S.L.. Snel A.M.
Comparison of the latencies between bone and air conduction in the auditory brain stem evoked potential
Eletroenc. Clin. Neurophys. 1983b. 56: 244-247

Boezeman E.H.J.F.. Bronkhorst A.W.. Kapteyn T.S.. Houffelaar A.. Snel A.M.
Phase relationship between bone and air conducted impulse signals in the human head
J. Acoust. Soc. Am. 1984. 76: 111-115

Boezeman E.H.J.F.. Kapteyn T.S.. Feenstra L.. Snel A.M.
Verification of the air-bone gap using cancellation and evoked responses
Audiology 1985. 24: 174-158

Coats A.C.. Martin J.L.
Human auditory nerve action potentials and brainstem evoked responses:
Effect of audiological shape and lesion location
Arch. Otolaryngol. 1977. 103: 605-622

Despland P.A.. Galambos R.
The auditory brainstem response is a useful diagnostic tool in the intensive care nursery.
Peadiatric Research 1980. 14: 154-158

Finitzo-Hieber T.. Hecox K.. Cone B.
Clinical applicability of the auditory-evoked response in neonates
Otolaryngology 1978. 86: ORL-638

Hicks G.E.
Auditory brainstem response sensory assessment by bone conduction masking
Arch. Otolaryngol. 1980. 106: 392-395

Hofmann G.. Flach M.
Hirnstammaudiometrie bei akustischer Reizung uber Knochen- und Luftleitung
Laryng. Rhinol. 1981. 60: 264-267

Hooks R. G.. Weber B.A.
Auditory brain stem responses of premature infants to bone- conducted stimuli: a feasibility study
Ear and Hearing 1984. 5: 42-46

Jerger J.. Mauldin L.
Prediction of sensorineural hearing loss from the brainstem evoked response
Arch. Otolaryngol. 1978. 104: 456-461

Jewett D.L.. Romano M.N.. Williston J.S.
Human auditory evoked potentials: possible brainstem components detected on the scalp
Science 1970. 167: 1517-1518

Jewett D.L.. Williston J.S.
Auditory evoked far fields averaged from the scalp of humans
Brain 1971. 94: 681-696

Kapteyn T.S.. Boezeman E.H.J.F.. Snel A.M.
Bone-conduction measurement and calibration using the cancellation method
J. Acoust. Soc. Am. 1983. 74: 1297-1299

Katz J.
Handbook of clinical audiology
Third edition 1985
The Williams and Wilkins Co. Baltimore

Kavanagh K.T., Beardsley J.V.
Brain stem auditory evoked response
III. Clinical uses of bone conduction in the evaluation of otologic disease
Ann. Otol. Rhinol. Laryngol. 1979, 88 (suppl. 58: 22-28)

Lary S., Briassoulis G., De Vries L., Dubowitz L., Dubowitz V.
Hearing thresholds in preterm and term infants by auditory brainstem responses
J. Paediatrics 1985, 107: 593-599

Mauldin L., Jerger J.
Auditory brainstem evoked responses to bone conducted signals
Arch. Otolaryngol. 1979, 105: 656-661

Olphen A.F.v.
Auditieve hersenstampotentialen bij de mens
Thesis 1983, Erasmus University Rotterdam

Selters W.A., Brackmann D.E.
Acoustic tumour detection with brain stem electric response audiometry
Arch. Otolaryngol. 1977, 103: 181-187

Sohmer H., Feinmesser M.
Cochlear and cortical audiology, conveniently recorded in the same subject
Isr. J. Med. Sc. 1970, 6: 219-223

Terkildsen K., Osterhammel P., Huis in 't Veld F.
Recording procedures for brainstem potentials
Evoked electrical activity in the auditory nervous system
Academic press, New York, San Fransisco 1978

Thornton A.R.D.
Properties of auditory brainstem responses
Revue de Laryngologie 1976, 87: 591-601

Zanten van G.A., Sauer P.J.J., Fetter W., Baerts W.
Brainstem electric response audiometry in preterm infants
Paper IVth International Symposium on Audiological Medicine
Tenerife nov. 8-13 1987

Chapter II

The relation between the pure tone audiogram and the click auditory brainstem response threshold in cochlear hearing loss

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Abstract

Auditory brainstem response thresholds for 209 ears with cochlear hearing loss were compared with the pure tone thresholds. It is shown that the pure tone threshold in the 2 to 4 kHz region has a one to one relationship with the auditory brainstem response threshold. Estimating the pure tone threshold from the auditory brainstem response threshold. the standard error of the estimate is 11 dB. A small part of this estimation error is due to errors in the measurement of the auditory brainstem response threshold and the mean of the pure tone thresholds at 2 and 4 kHz. The major part is due to unknown factors. that are involved in the physiological relationship between the two thresholds.

Resumé

Relation entre l'audiogramme et le seuil des réponses évoquées du tronc cérébral au clic dans les surdités de perception

Dans 209 oreilles présentant une surdité de perception. les seuils des potentiels évoqués du tronc cérébral évoqués par un clic ont été comparé avec les seuils subjectifs de l'audiogramme. En moyenne le seuil subjectif dans la région 2 à 4 kHz est égal au seuil objectif. L'estimation d'un seuil subjectif à partir d'un seuil objectif se fait avec une marge d'erreur de 11 dB. Les erreurs de détermination des deux seuils sont négligeable. La plus grande partie de cette marge est due a des facteurs inconnus dans la relation physiologique entre ces deux seuils auditifs.

Introduction

Brainstem electrical response audiometry is generally used to obtain data concerning the hearing of patients. in those cases where subjective audiometry is not possible or is unreliable. The subjective pure tone audiogram is the most generally used measure of the human hearing threshold. and the only suitable standard for comparison with the objective auditory brainstem response threshold.
However. these two methods of threshold determination are basically different. The measurement of a pure tone threshold involves the entire auditory system. from the external canal to the cerebral cortex where the auditory sensation is registered. In brainstem electrical response audiometry. on the other hand. electrical phenomena are recorded that are generated up to the midbrain level. Another principal difference is the stimulus. In pure tone audiometry this is a continuous tone (duration >300 ms) of variable frequency. In brainstem electrical response audiometry the stimulus commonly used is a click (duration about 0.1 ms). the

spectrum of which contains all audible frequencies. Some researchers try to obtain frequency-specific brainstem responses by using tone pips. Though such a stimulus is more frequency specific, it has been shown by Kileny (1981) that the responses are much less frequency-specific than the nature of the stimulus would imply. This method will not be used here. Despite the differences mentioned above, the relationship between the audiogram and the auditory brainstem response threshold is of major interest to the clinician.

To our knowledge only four papers have been published in which a comparison between the brainstem response threshold and the pure tone audiogram has been based on a sufficiently large number of patients. Coats and Martin (1977), in an elaborate study, compared electro-cochleographic responses, brainstem responses, and pure tone audiograms obtained from normal ears and ears with perceptive hearing loss. They were primarily interested in the latencies of the brainstem response peaks. They also compared the auditory brainstem response thresholds with the pure tone thresholds of 53 ears with cochlear impairment and studied the correlation between these thresholds. The auditory brainstem response threshold correlated best (r=0.65) with the mean of the pure tone thresholds at 4 and 8 kHz. The slope of the regression line was about 0.9 for the pure tone frequencies 1 and 2 kHz (table I). The standard error of the estimate was not given.

Table I. Regression analyses of the relation between the auditory brainstem response threshold, ABR-T, and the pure-tone threshold, PTT, in four studies.

Regression analysis data	Jerger and Mauldin (1978)	Coats and Martin (1977)	Bellman et al. (1984)	Present study
Maximum correlation coeff. of PTT with ABR-T	0.48 (at 1-2-4 kHz)	0.65 (at 4-8 kHz)	0.85 (at 2-4 kHz)	0.93 (at 2-4 kHz)
Most favorable slope of the regression line	0.63 (at 4 kHz)	ca. 0.9 (at 1-2 kHz)	0.90 (at 4 kHz)	1.10 (at 2-4 kHz)
Minimum standard error of the estimate, dB	15.8 (at 1-2-4 kHz)		19.0 (at 1-2-4 kHz)	11.1 (at 2-4 kHz)

Jerger and Mauldin (1978) published an extensive study on the relationship between the pure tone thresholds and the auditory brainstem response threshold. They investigated 275 ears with cochlear hearing loss. They found the best correlation (r=0.48) was with the mean of the pure tone thresholds at 1, 2, and 4 kHz. This mean value also had the smallest standard error (15.8 dB).

The slope of the regression line was steepest (0.63) for the regression on the 4 kHz pure tone threshold. Kavanagh and Beardsley (1979) tested 23 ears with cochlear hearing loss and calculated the difference between the pure tone audiogram and the brainstem response threshold. They found this difference to be

smallest for pure tone frequencies above 2000 Hz. ranging from 0 to 40 dB; 8 of the 23 ears showed a difference of more than 15 dB. Bellman et al.(1984) compared the pure tone and auditory brainstem response thresholds of 56 ears. They found a maximum correlation coefficient. r= 0.85. with the mean of the pure tone thresholds at 2 and 4 kHz. The smallest. thus most favourable. mean difference between the two thresholds was 14.6 dB. for the mean of the pure tone thresholds at 1. 2. and 4 kHz. They also determined the slope of the regression line: this slope was 0.9 for the regression of the response threshold on the 4 kHz pure tone threshold. The smallest standard error of the estimate. 19 dB. was in the regression on the mean of the pure tone thresholds at 1. 2. and 4 kHz. The range of the pure tone losses involved was 115 dB.
Summarizing the literature. it can be said that the pure tone audiogram and the auditory brainstem response threshold correlate best at the high frequencies. This is in line with our clinical experience. However. the high standard errors of the estimate. the deviation from 1 in the slopes of the regression lines and the low correlation coefficients seen in the literature (see Table I) seem to indicate that the auditory brainstem response threshold is not a very accurate way of assessing hearing sensitivity. This is not in line with our clinical experience. and we felt the need to collect our own reference data. especially with regard to the following three questions:

1. What part of the pure tone audiogram correlates best with the auditory brainstem response threshold?

2. How accurate is the prediction of the pure tone threshold(s) from the auditory brainstem response threshold?

3. To what extent is the accuracy of this prediction affected by measurement errors in both threshold determination methods?

This particular study is limited to cochlear hearing loss.

Procedures

Subjects

Patients with a perceptive hearing loss were recruited as subjects. Most of them had suffered hearing impairment for many years and were asked to participate at one of their regular control visits. The subjects had to be able to produce a reliable audiogram and the hearing loss had not to be of the retrocochlear type. In most cases retrocochlear pathology was excluded by the clinical history. ENT examination and neurological examination (in this study limited to the examination of the cranial nerves). Where there was any suspicion of retrocochlear pathology. stapedial reflex tests. electronystagmography and sometimes computer-tomographic X-ray scanning were used to enable further selection. If the results were inconclusive. the patient was excluded from the test group. Only patients whose audiograms showed a mean air-bone gap less than 7.5 dB and no air-bone gap exceeding 10 dB were included in the test group. Apart from excluding retrocochlear pathology and conductive hearing loss. no selection was made on etiology. So the etiologies of the hearing impairments involved in the test group were presbyacusis. Ménières disease. hereditary cochlear hearing loss. and ototoxic medication. Subjects were selected for whom the mean of the pure tone thresholds at 2 and 4 kHz were in the 0-120 dB range. This criterion was adopted from the literature as presented in the former section. We made an effort to obtain a uniform distribution of the losses in this range. The test group consisted of 136 individuals. 68 males and 68 females. Threshold data were collected for 209 ears. In order to calculate the measurement errors of the thresholds. another 10 subjects were selected and their 20 ears were investigated twice. within a period of one week.

Equipment

The click stimulus was generated with a Wavetek 186 signal generator. The click had an alternating polarity. an electrical duration of 100 microsec and a repetition frequency of 20 Hz. The stimulus was presented by a TDH-39 headphone. Click levels are given in dBnHL (0 dB was defined as the mean subjective threshold in three normal-hearing subjects: this corresponded to 48 dBpeSPL). The electrical input to the headphone. the sound pressure waveform. and the stimulus spectrum are shown in fig.1.

A two-channel recording was made using vertex-mastoid electrode pairs. A forehead electrode served as the ground electrode. Common Ag-AgCl cup electrodes were used. Electrode impedances were kept below 2 kΩ. The electrode signals were multiplied 10.000 times in the 10-4000 Hz frequency band (filter slopes 24 dB/oct). A Datalab DL 4000 signal averager was used for averaging 2048 post stimulus periods of 15 ms. containing 512 samples each. Artefact rejection was used: post stimulus periods containing samples that fell outside the range -12.5 to +12.5 microVolts were not processed. The averaged responses were recorded on paper.

For pure tone audiometry a conventional clinical audiometer was used. with maximum output levels of 120 dBHL in the frequency region concerned.

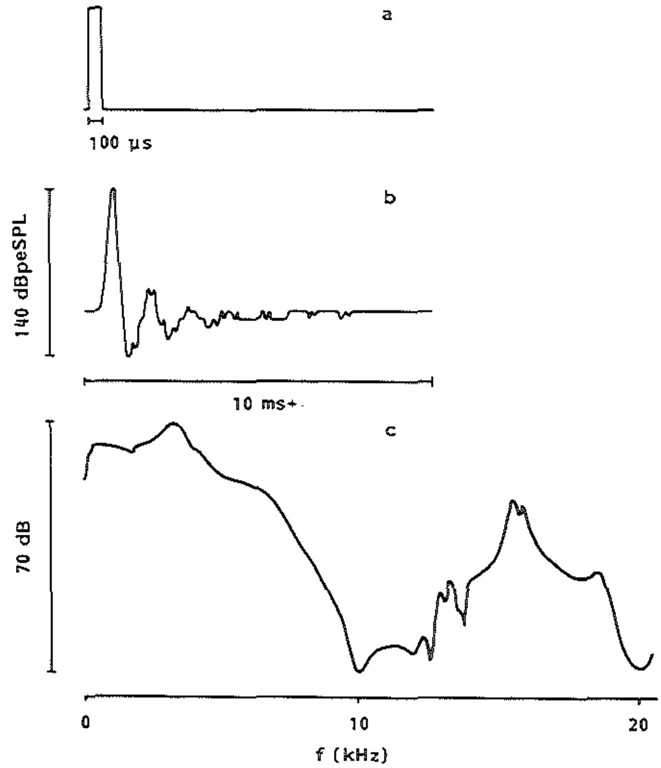

Fig. 1

Waveforms of the electrical input to the headphone -panel(a)-, of the stimulus sound pressure -panel(b)-, and the stimulus spectrum of the click -panel(c)-.

Threshold determination

Pure tone audiometry was done using the conventional method. The acquisition of auditory brainstem responses started at a stimulus level of 90 dBnHL. Depending on the result, the stimulus level was increased or decreased in steps of 10 or 20 dB, until the threshold level was approached. The threshold level was defined as the lowest stimulus level with a peak V in the response. The threshold level was determined in 5 dB steps. Reproducibility of the responses at, below and above the threshold level was tested.

Data processing

Both pure tone thresholds and the auditory brainstem response thresholds were processed with the help of a statistical computer program-package (SPSS). The correlation of the response threshold with the pure tone threshold was calculated.

as well as their mean difference and the standard deviation of the difference. Both the relation between the response threshold and the pure tone thresholds and between the response threshold and the mean values of pure tone thresholds were studied by means of regression analysis.

In the group of 10 patients who were investigated twice, the difference between the first and the second results was calculated for both thresholds. The standard deviation of these test-retest differences was computed. The inaccuracy of each threshold was calculated by dividing this standard deviation by √2.

Results

Figure 2 shows the distribution of the mean of the pure tone thresholds at 2 and 4 kHz. In 5 ears with no measurable pure tone threshold at one of these frequencies, 125 dBHL was used in the calculations. Figure 2 shows a fairly uniform distribution, which was the aim of our patient selection procedure. As the "3 kHz pure tone loss" was the only loss criterion for inclusion in the test group, all kinds of audiogram shape are present in the test group. Figure 3 shows two examples of auditory brainstem response patterns, and the corresponding pure tone audiograms.

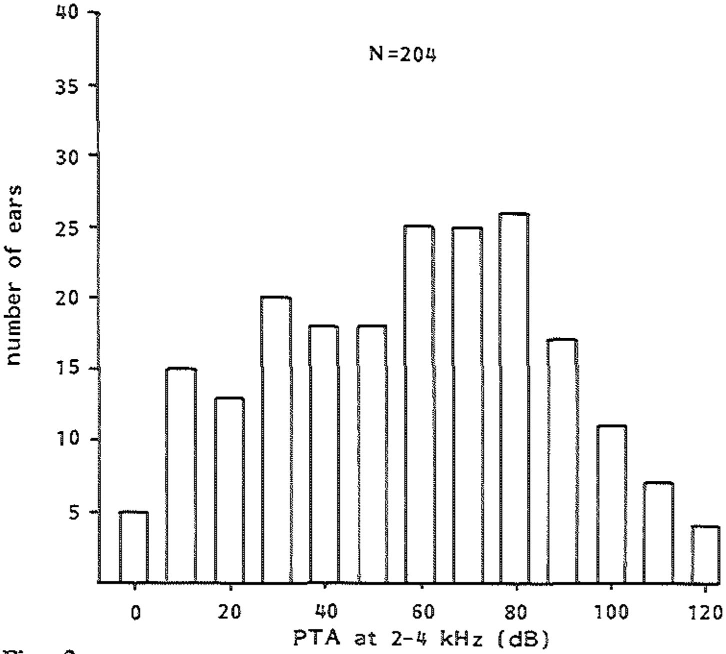

Fig. 2

Distribution of the 204 ears with a measurable auditory brainstem response over the mean of the pure tone hearing loss at 2 and 4 kHz (PTA).

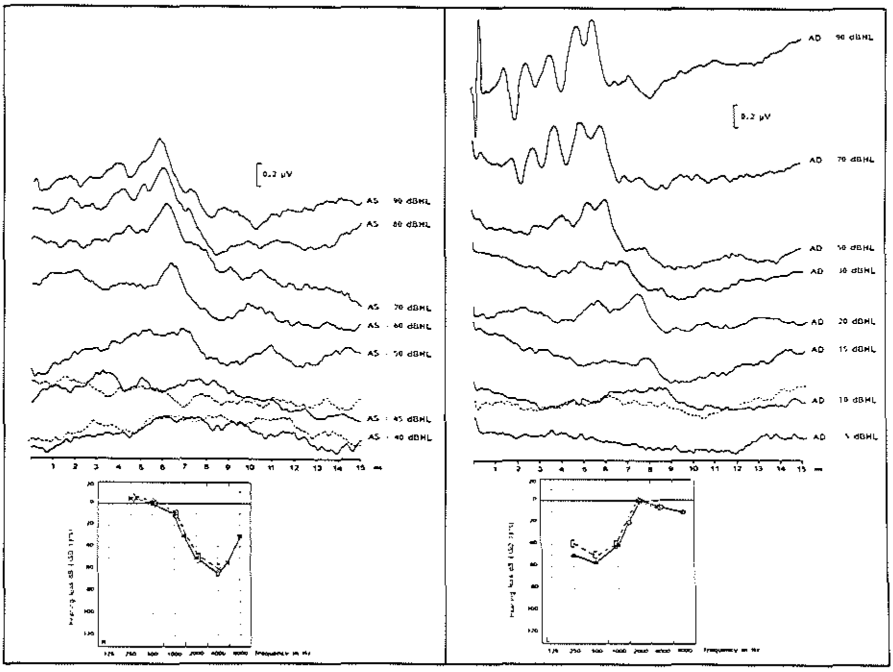

Fig. 3

Two examples of auditory brainstem response patterns and their corresponding pure tone audiograms. (a) The audiogram shows a high frequency loss; the auditory brainstem response threshold is 50 dBnHL. (b) The audiogram shows a low frequency loss: the auditory brainstem response threshold is 10 dBnHL.

The mean difference between the auditory brainstem response threshold and the corresponding pure tone threshold is shown in fig.4 (the exact data are also given in table II). The figure shows that the absolute mean difference is smallest (1.9 dB) for the mean of the pure tone thresholds at 2 and 4 kHz.

Table II. Statistical results for the difference between the auditory brainstem response threshold and the pure-tone threshold, and results of the regression analysis of the relations between the ABR-T and the separate frequencies of the pure-tone audiogram, the mean of the pure-tone thresholds at 2 and 4 kHz and the mean of 1, 2 and 4 kHz.

Relations PTA-ABR-T	**Pure-tone frequency (kHz)**							
	0.25	**0.50**	**1.0**	**2.0**	**4.0**	**8.0**	**2-4**	**1-2-4**
Mean difference, dB	19.0	15.4	11.1	5.0	−6.5	−11.9	−1.9	3.3
Standard deviation of difference, dB	25.0	22.8	18.2	13.3	14.1	18.6	11.6	11.3
Correlation coefficient	0.59	0.68	0.82	0.91	0.89	0.81	0.93	0.92
Slope of the regression line	1.11	1.11	1.13	1.14	1.12	1.14	1.10	1.06
Standard error of the estimate, dB	22.4	20.9	17.1	12.6	13.4	17.1	11.1	11.0

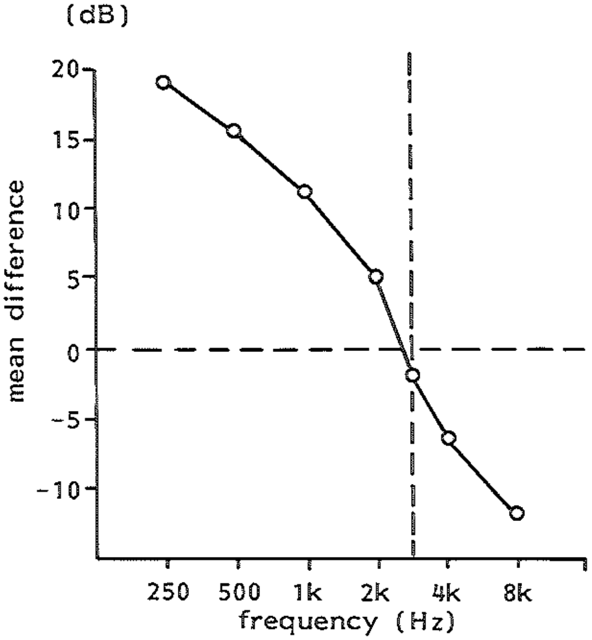

Fig. 4
The mean difference between the auditory brainstem response threshold and the pure tone loss as a function of the pure tone frequency.

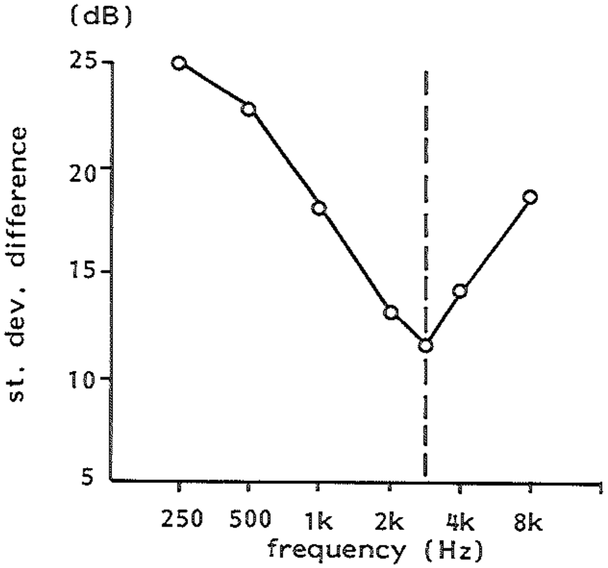

Fig. 5
The standard deviation of the difference between the auditory brainstem response threshold and the pure tone threshold as a function of the pure tone frequency.

The standard deviation of this difference for the different pure tone frequencies is shown in fig.5. It shows that the standard deviation is at its lowest, 11.6 dB, for the mean of the thresholds at 2 and 4 kHz. In fig.6 the correlation between the auditory brainstem response threshold and the pure tone threshold is drawn as a function of the pure tone frequency. This correlation is highest, 0.93, for the mean of the pure tone thresholds at 2 and 4 kHz.

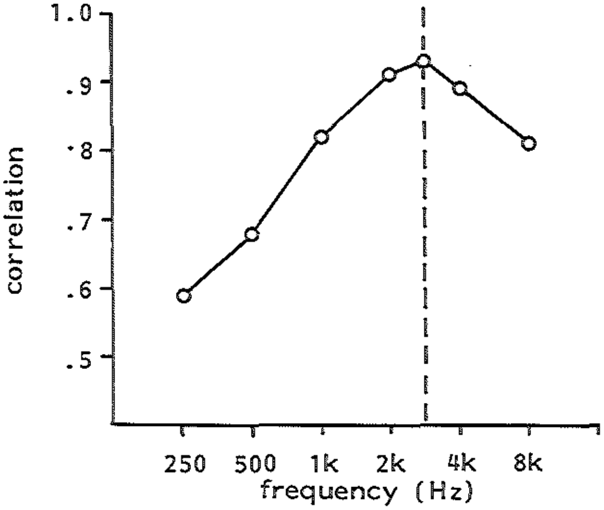

Fig. 6
The correlation coefficient for the auditory brainstem response threshold and the pure tone threshold as a function of the pure tone frequency.

From the test-retest data it appeared that the inaccuracy of the mean of the pure tone thresholds at 2 and 4 kHz was 2.9 dB. The inaccuracy of the auditory brainstem response threshold measurement was 3.7 dB.

A scatterplot of the mean of the pure tone thresholds at 2 and 4 kHz against the auditory brainstem response threshold is given in fig.7, together with the regression line as well as the regression coefficients.[1]

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[1] In fact the regression analysis was done in both directions, yielding two slope coefficients. Because both thresholds are measurements with about equal inaccuracy, the given slope coefficient is the mean of the two slope coefficients.

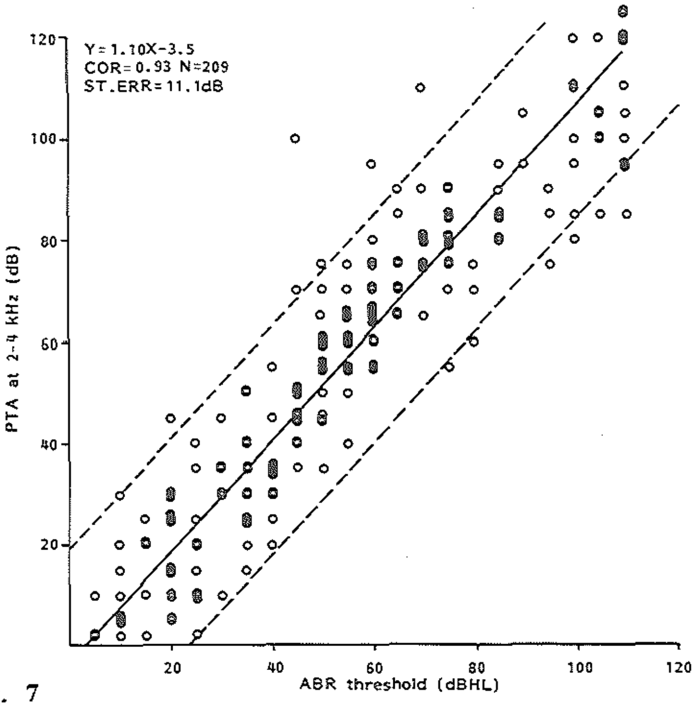


Fig. 7

Scatter diagram of the mean of the pure tone thresholds at 2 and 4 kHz (PTA) as a function of the auditory brainstem response threshold (ABR-T). (The two values with a pure tone loss of 125 dBHL and three values with 120 dBHL represent ears with pure tone losses at 2 and/or 4 kHz of over 120 dB and a recordable peak V in the auditory brainstem response at 110 dBnHL).

The data are evenly spread around this regression line. The standard error of the estimate in the regression analysis is 11.1 dB.

In fig.8 the percentage of ears which give a peak V in the auditory brainstem response is drawn as a function of the mean of the pure tone thresholds at 2 and 4 kHz. Up to 100 dBHL a peak V was found in the auditory brainstem response in all but 1 cases. In 19 of the 34 cases where the mean of the pure tone thresholds at 2 and 4 kHz was above 100 dBHL, no peak V could be detected. These cases have not been included in the statistical computations.

Discussion

Figure 4 shows that the difference between the pure tone threshold and the brainstem response threshold is zero at a frequency between 2 and 4 kHz. At lower frequencies the difference becomes strongly positive, for higher frequencies negative. The absolute difference at 8 kHz is about the same as at 1 kHz. As is shown in fig.5, the standard deviation of the mean difference is lowest, 11.6 dB for the mean of the pure tone thresholds at 2 and 4 kHz. It is also for this pure tone threshold that the correlation coefficient is highest (r=0.93). Taking into account that all ears had cochlear hearing loss, which only differed in degree, we may conclude that the part of the cochlea sensitive to about 3 kHz dominates the auditory brainstem response threshold for click stimulation.

Table I shows both the statistical figures mentioned above, and comparable ones from the literature. The finding of this study that the mean of the pure tone thresholds at 2 and 4 kHz correlates best with the auditory brainstem response threshold is roughly in line with the findings in the three papers quoted. Jerger and Mauldin (1978) found that the auditory brainstem response threshold correlated best with the mean of the pure tone thresholds at 1, 2, and 4 kHz, while Bellman et al.(1984) found the best correlation for the mean of the pure tone thresholds at 2 and 4 kHz, as we did. The larger influence of the 8 kHz region, found by Coats and Martin (1977), deviates slightly from these results. However, table I also shows that there are rather large differences in the magnitude of the correlation between the different studies. A correlation coefficient of 0.48, found by Jerger and Mauldin (1978), and of 0.65, found by Coats and Martin (1977), is considerably less encouraging for the clinical use of the auditory brainstem response threshold, than the 0.85 found by Bellman et al.(1984), and the 0.93 established in the present study. The standard error of the estimate in the regres-

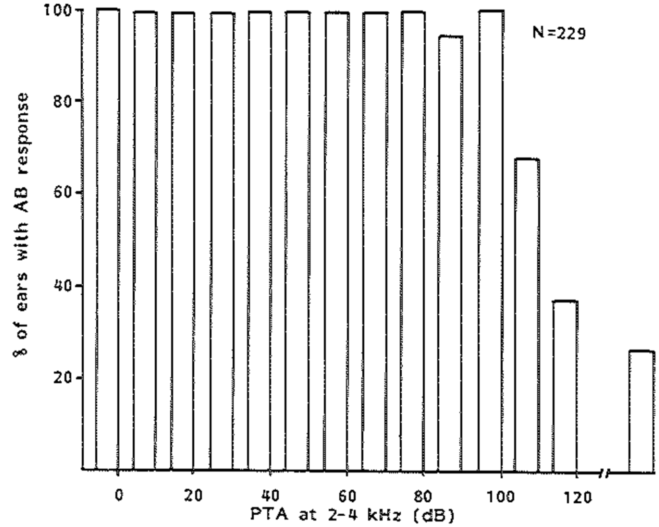


Fig. 8

The percentage of ears with a recordable auditory brainstem response threshold as a function of the mean of the pure tone losses at 2 and 4 kHz. The total number of ears tested was 229. The data for 20 ears with no recordable peak V in the auditory brainstem response were not included in further computations.

sion analysis indicates the degree of accuracy of the prediction of the pure tone threshold from the auditory brainstem response threshold. The figure of 11.1 dB in this study is considerably more favourable than the 15.8 dB in Jerger and Mauldin's (1978) study, and the 19 dB in study by Bellman et al.(1984). Of the four studies referred to in the introduction only Bellman et al. mentioned the use of artefact rejection. Not using artefact rejection might result in larger differences between the objective and subjective threshold. The large standard error of Bellman et al., 19 dB, might have four causes: the time lapse of up to 8 years between the measurement of the two thresholds in an unspecified number of cases, the small number of individuals in the test group, the fact that different types of hearing loss were involved in that study, and also the fact that the follow-up audiograms were in some cases made in other centers.

The slope of the regression line for our material is near unity, as it was in the study by Bellman et al., but this was not the case in Jerger and Mauldin's study, where the slope was 0.6. In our material the auditory brainstem response threshold itself is the best estimate for the mean pure tone threshold at about 3 kHz, and no correction factor is needed.

To obtain a 95% reliability in the prediction of the pure tone threshold from the auditory brainstem response threshold a region of 4 times the standard error of the estimate has to be taken into account. So, for instance if one measures an auditory brainstem response threshold at 60 dBnHL, this means that the pure tone threshold at 3 kHz will be in the range 38 to 82 dBHL with 95% probability. One has to keep in mind, however, that two different measurements were correlated to arrive at this result. Both measurements contain their own inaccuracy. As the slope of the regression line is near unity, both measurement inaccuracies contribute equally to the standard error of the estimate. These measurement inaccuracies are 2.2 dB for the pure tone and 3.1 dB for the brainstem result. The intra-individual variance of these thresholds is thus quite low compared to the standard error of the estimate. The major part of this error must be caused by the inter-individual variance. We can therefore conclude that there are other, still unknown, factors that are more important. These factors cause the less than perfect linkage between the auditory brainstem response threshold and the pure tone audiogram. These factors are probably related to the fact that basically different thresholds are involved.

The contrast between our clinical impression and the reports from the literature was the motive for this study. It has been shown that, provided that artefact rejection is used, the stepsize in threshold assessment is 5 dB, reproducibility of the response peaks at levels near threshold is tested and the responses are always judged by the same experienced observers, then brainstem response audiometry is a valuable tool for threshold assessment. The method can, as far as the high frequencies are concerned, compete with electrocochleography using tone pips. Spoor and Eggermont (1976) found a correlation coefficient of 0.91 and 0.92 for 2 and 4 kHz respectively. The slopes of the regression lines for these frequencies were 0.95 and 0.91 respectively. The histograms in that study suggest a standard error of the estimate of about the same magnitude as ours. The fact, that Brainstem Response Audiometry is a noninvasive method makes it in our clinical setting the method of first choice.

Conclusions

In cochlear hearing loss

1. The auditory brainstem response threshold correlates best with the mean of the 2 and 4 kHz pure tone thresholds. The correlation coefficient is 0.93.

2. The relationship between the auditory brainstem response threshold and the mean of the pure tone thresholds at 2 and 4 kHz is one to one.

3. The standard error of the estimate in the relation between the mean of the pure tone thresholds at 2 and 4 kHz and the auditory brainstem response threshold is 11.1 dB.

4. This estimation error is only partly due to errors in the measurement of the auditory brainstem response threshold and of the mean of the pure tone thresholds at 2 and 4 kHz; the error is mainly due to unknown factors involved in the relationship between the two thresholds.

References

Bellman S.. Barnard S.. Beagley H.A.
A nine year review of 841 children tested by transtympanic electrocochleography
J. of Laryngol. and Otol. 1984. 98: 1-9.

Coats A.C.. Martin J.L.
Human auditory nerve action potentials and brainstem evoked responses: Effect of audiogram shape and lesion location
Arch. Otolaryngol. 1977. 103: 605-622.

Jerger J. Mauldin L.
Prediction of sensorineural hearing loss from the brainstem evoked response
Arch. Otolaryngol. 1978. 104: 456-461.

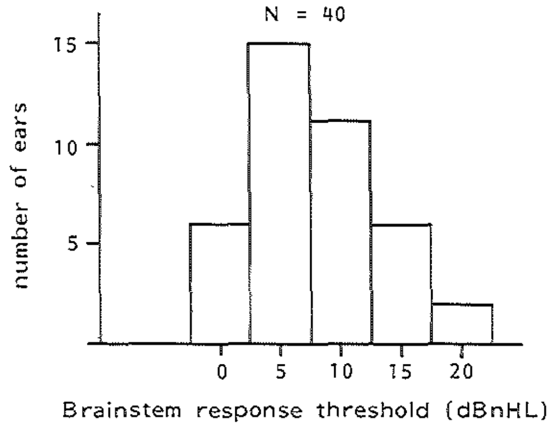
Kavanagh K.T.. Beardsley J.V.
Brainstem auditory evoked response II: clinical application in the assessment of patients with organic hearing loss
Ann. Otol. Rhinol. Laryngol. 1979. 88. suppl. 58: 11-21.

Kileny P.
The frequency specificity of tone-pip evoked audiometric brainstem responses
Ear and Hearing 1981. 2: 270-275.

Spoor. A.. Eggermont. J.J.
Electrocochleography as a method for objective audiogram determination
Hearing and Davis. Hirsh. Eldredge and Silverman (Eds). Eden Publ. Cie.. St. Louis. Mo. 1976

Appendix to chapter II

Brainstem response threshold in normal hearing



Number of ears as a function of the brainstem response threshold in normal hearing.

The testgroup consisted of 12 male and 10 female subjects. In this group 40 ears were tested. Hearing was considered to be normal if the mean of the air conduction tone threshold did not exceed 7.5 dBHL and no tone threshold exceed 15 dBHL.

The mean brainstem response threshold is 8.0 dBnHL and the standard deviation is 5.5 dBHL.

Chapter III

Inaccuracies in the measurement of auditory brainstem response data in normal hearing and cochlear hearing loss

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Audiology. accepted October 1987

Abstract

In a test-retest experiment inaccuracies in the measurement of the peak latencies and threshold of the auditory brainstem response were determined for a group with normal hearing and for a group with cochlear hearing loss. The inaccuracy of the auditory brainstem response threshold is less than 4 dB in both groups. The inaccuracy in latency was measured as a function of stimulation level. In both groups the latency inaccuracy of peak V varies from 0.1 ms at levels well above threshold to 0.2 ms near the response threshold. Analysis of variance showed that in subjects with normal hearing the intra- and inter-individual variabilities of the peak V latencies contribute about equally to the total variance at all stimulation levels. The implications that these findings have for the determination of the horizontal shift of the latency-Level curve are discussed.

Résumé

Imprécision des réponses evoquées du tronc cerebral chez les sujets normaux et dans les surdités cochléaires

Par une expérience de test et de retest les inexactitudes des latences des pics des potentiels évoqués auditifs du tronc cérébral et l'inexactitude du seuil de ce potentiel sont determinées pour un groupe des sujets normaux et pour un groupe des patients avec une surdité de perception. Dans les deux groupes, l'inexactitude du seuil du potentiel évoqué auditif du tronc cérébral est inférieur à 4 dB. L'inexactitude des latences des pics dépend du niveau de la stimulation. L'inexactitude de la latence du pic V est 0.1 ms aux niveaux fort au-dessus du seuil et augmente jusqu'à 0.2 ms aux niveaux jusqu'au-dessus du seuil. Une analyse de la variance de la latence du pic V dans le groupe normal démontre que la variance intra-individuelle et la variance inter-individuelle sont approximativement de grandeur égale pour tous les niveaux de la stimulation. Les implications de ces inexactitudes sont discutées pour la determination du déplacement horizontal de la courbe de la latence et de l'intensité.

Introduction

The two parameters which are used for clinical assessment in brainstem audiometry are the peak latencies (of the peaks I. III and V) and the response threshold. Two goals can be distinguished: measurement of hearing level and detection of retrocochlear pathology.

For the detection of retrocochlear pathology the latencies of peaks I. III and V are used. The combination of the brainstem response threshold and the peak latencies gives information for audiometric evaluation.

For audiometric interpretation of brainstem responses the latency-Level curve (l(L) curve) is a useful tool. The entire l(L) curve shifts by the conductive component of a hearing loss in a direction parallel to the level axis (McGee and Clemis (1982)). The reliability of the peak latencies at all stimulation levels becomes important. if the latency shift is to be used as a measure of the conductive hearing loss and as such is repeatedly determined when following the course of a disease and/or therapy. It is thus essential to be able to differentiate between the latency shift caused by a real change in middle ear function and that caused by inaccuracies in the measurement. Since the amount of conductive hearing loss is measured by the shift of the l(L) curve in the level direction (i.e. in dB) inaccuracies in the measurement of the peak latencies (in ms) have to be converted into equivalent inaccuracies in the stimulation level (in dB).

It is our impression that in clinical measurement near the threshold the signal to noise ratio becomes less favourable and the peak V tends to become wider. This phenomenon means that the determination of the latency of peak V is less accurate at low stimulation levels. As. when determining the overall latency shift of the curve. errors in the measurement have to be converted into errors in the stimulation level. the measurement inaccuracy of the latency is just as relevant at low stimulation levels.

The literature on inter-test variability of brainstem response data is rather scarce and does not include data on all stimulation levels. Edwards et al.(1982) tested the variability of the peak V latency in 10 healthy young adults with normal hearing. The procedure was repeated after approximately 150 days. In this experiment one stimulation level of 72 dBnHL was used. The intra-subject standard deviation of the distribution of the peak V latency differences. calculated from their data is 0.14 ms.

Rosenhammer et al.(1978) tested 6 subjects with normal hearing on two occasions with an inter-test period of 6 months. They used a stimulation level of 80 dBSL. The standard deviations of the distributions of the test-retest differences for the latencies of peak I. III and V were 0.08. 0.14. and 0.14 ms respectively.

The measurement inaccuracy of the auditory brainstem response threshold in subjects with cochlear hearing loss has been demonstrated to be 3.1 dB (chapter II). No data were found in the literature concerning the inaccuracy of the response threshold in normal hearing.

In the literature on the inaccuracies in the measurement of the peak latencies. the only data found for normal hearing were at high stimulation levels. As far as the response threshold is concerned. the only published data on measurement inaccuracies were for cochlear hearing loss. Thus the aim of this study is to find answers to the following questions:

1. What is the inaccuracy in measurement of the peak latencies of auditory brainstem responses as a function of the stimulation level in normal hearing?

2. Does cochlear hearing loss influence the inaccuracy of the peak latencies?

3. What is the inaccuracy in the measurement of the brainstem response threshold in normal hearing?

Procedures

Experimental conditions and measuring methods

The equipment used was similar to that described in chapter II. summarized in table I of this chapter. Pure tone audiometry was performed according conventional method. testing all octave frequencies between 250 Hz and 8 kHz.

Table I. Summary of data on measurement technique

Click polarity	alternating
Click duration	100 μs
Click repetition frequency	20 Hz
Headphone	TDH-39
Electrode impedances	< 2 kΩ
Filter bandwidth	10-4000 Hz
Filter slopes	24dB/oct.
Number of runs	2048
Artifact rejection levels	-12.5 to $+ 12.5$ μV
Time resolution	29.3 μs

Auditory brainstem responses were recorded. starting at a stimulus level of 100 or 90 dBnHL. Depending on the result. the stimulus level was reduced in steps of 10 or 20 dB until the threshold level was approached. The threshold level was defined as the lowest stimulus level at which a reproducible peak V could be identified. The threshold level was determined using 5 dB steps. All responses were assessed by 2 experienced observers [F.v.d.D.. M.B.]. The results of the first session were not referred to during the assessment of the second session.

Patient selection

For this study test-retest data were obtained from a group of healthy young adults with normal hearing and from a group of adults with varying degrees of cochlear hearing loss. The data measured were the brainstem response threshold. the latencies of the peaks I. III and V. and their inter-peak latencies at each stimulation level.

The test group with normal hearing comprised of 6 male and 5 female subjects. randomly selected from a group of healthy young adults with normal hearing. All subjects in the normal hearing group had pure tone thresholds that did not exceed 15 dBHL at any frequency and the loss averaged over all frequencies between 250 Hz and 8 kHz did not exceed 7.5 dB.

The group of patients with cochlear hearing loss was selected according to the criteria described in chapter II. These criteria are that the air-bone gap averaged over all frequencies should be smaller than 7.5 dB and that it should not exceed 10 dB at any frequency. Etiology played no part in the selection. The means of the pure tone thresholds at 2 and 4 kHz in this group ranged from 20 dBHL to 70 dBHL; the attenuation step size of the stimulation level varied from 20 to 5 dB.

The time lapse between the test and retest examination was at least 7 days.

Results

In 6 male and 5 female subjects with normal hearing, threshold and supra-threshold data were collected from 20 ears. In the test population of 4 male and 5 female subjects with cochlear hearing loss similar data were collected from 18 ears.

To ascertain whether parametrical statistical tests were applicable, all distributions of test-retest differences were tested for normality by means of the Kolmogorov-Smirnov one sample test. As in Thornton (1975), it appeared that, with one exception, none of the tested distributions was significantly different from normal ($p<0.05$). The distribution of the response threshold test-retest differences deviated from normal because of skewness. Nevertheless, the distribution was tested by the same parametrical statistical test as all the others, to produce data of the same type.

Paired T-tests were done to determine wether there were statistically significant differences between the test and retest measurements of brainstem thresholds and of all peak latencies. There was no significant difference in any of the measurements ($p>0.1$).

In order to find whether there was any interrelationship between the left and right ears within subjects an analysis of variance was carried out on these variables. The distributions of the test-retest differences over the subjects appeared to be identical for left and right ears and thus equal to that for all ears (F-value:0.009; significance:0.92). In further analyses the data from the right and left ears were considered to be independent.

The standard deviation of the distribution of a variable that is measured a large number of times is by definition the measurement inaccuracy. The distribution of difference between one measurement (test) and another (retest) of a variable has a mean of zero and a standard deviation that is a factor $\sqrt{2}$ larger than the measurement inaccuracy. Assuming that the measurement inaccuracy is similar for all subjects. we calculated the inaccuracies in measurement by dividing the standard deviations of the distributions of the test-retest difference by $\sqrt{2}$.

Table II. Inaccuracies (in ms) in measurement of the latencies of peak I, III and V in normal hearing and cochlear hearing loss as a function of the stimulation level

Stim. level	Normal hearing			Cochlear hearing loss		
dB nHL	LI	LIII	LV	LI	LIII	LV
100	0.07 n = 19	0.05 n = 20	0.08 n = 20			
90	0.10 n = 18	0.06 n = 20	0.08 n = 20	0.07 n = 12	0.07 n = 14	0.09 n = 18
80	0.08 n = 18	0.05 n = 19	0.06 n = 19			
70	0.08 n = 16	0.06* n = 19	0.09* n = 19	0.08 n = 5	0.11* n = 10	0.13* n = 18
60	0.08 n = 15	0.08 n = 19	0.07 n = 20			n = 4
50	0.09 n = 6	0.16 n = 17	0.10 n = 20		n = 1	0.13 n = 10
40	n = 2	0.18 n = 14	0.12 n = 20		n = 1	n = 2
30	n = 2	0.16 n = 12	0.12 n = 19			n = 4
20	n = 1	0.12 n = 6	0.14 n = 20			n = 3
10			0.17 n = 14			
5			0.31 n = 5			

* $p < 0.05$: significant difference between the two groups. n = Number of ears.

Table II shows for both test groups the inaccuracies of the latencies of the peaks I. III and V as a function of the stimulation level in dBnHL. The inaccuracies of the peak latencies in the normal hearing group appear to be less than 0.1 ms for stimulation levels above 50 dBnHL. Below this level the inaccuracies tend to increase to about 0.2 ms or more as the stimulation level decreases. In table III similar data are given for the inter-peak latencies. The differences between the inaccuracies for the two populations for corresponding experimental conditions were tested for significance. This was done using an F-test in all cases where the data for normal hearing and cochlear hearing loss were based on more than 4 individual ears. At 70 dBnHL stimulation level the inaccuracies of the peak III and peak V latencies are significantly smaller in subjects with normal hearing than in those with cochlear impaired hearing ($p<0.05$). The same phenomenon is apparent in the corresponding I-V and III-V latencies. as shown in Table III.

Table III. Inaccuracies (in ms) in measurement of the I-III, I-V and III-V latencies for normal hearing and cochlear hearing losses as a function of the stimulation level (in dBnHL)

Stim. level	**Normal hearing**			**Cochlear hearing loss**		
dBnHL	**I-III**	**I-V**	**III-V**	**I-III**	**I-V**	**III-V**
100	0.10 n = 19	0.08 n = 19	0.08 n = 20			
90	0.13 n = 18	0.13 n = 18	0.08 n = 20	0.13 n = 11	0.09 n = 12	0.12 n = 18
80	0.08 n = 18	0.10 n = 18	0.08 n = 19			
70	0.06 n = 16	0.06* n = 16	0.09* n = 19	0.06 n = 5	0.10* n = 5	0.14* n = 10
60	0.09 n = 15	0.06 n = 15	0.09 n = 19			
50	0.08 n = 6	0.11 n = 6	0.11 n = 17			n = 1
40	n = 2	n = 2	0.15 n = 15			n = 1
30			0.15 n = 12			
20			0.15 n = 6			

$p < 0.05$; significant difference between the two groups. n = Number of ears.

The inaccuracy in measurement of the brainstem response threshold in subjects with normal hearing was found to be 3.8 dB.

Discussion

This study shows (table II) that in normal hearing the inaccuracy of the latency of peak V increases from about 0.1 ms at high stimulation levels to about 0.2 ms near threshold. This finding is comparable with results obtained from the literature when the standard deviations of the test-retest difference distributions. described in the literature section of the introduction. are divided by $\sqrt{2}$. Inaccuracies of 0.06. 0.09. and 0.09 ms were computed for the latencies of peaks I. III and V respectively at 80 dBSL stimulation level using the data of Rosenhammer et al.(1978). At 70 dBnHL a peak V latency inaccuracy of 0.09 ms can be computed from the report of Edwards et al.(1983). Thus for high stimulation levels the data from this study are consistent with the literature.

Further inspection of table II shows that the inaccuracies in normal and impaired hearing are about equal at 90 dBnHL stimulation level. At 70 dBnHL the inaccuracies for peak III and V are significantly smaller in subjects with normal hearing than in those with cochlear hearing loss. We assume that this is caused by the fact that 70 dBnHL is a close to the threshold level for a number of the measured ears with cochlear hearing loss. This is illustrated in table IV. which shows the inaccuracies as a function of the stimulation level relative to the response threshold (in dBRTL). The inaccuracies in cochlear hearing loss appear to be just as small as. and for some values significantly smaller than those. in normal hearing.

Table IV. Inaccuracies (in ms) in the measurement of the peaks I, III and V latencies for normal hearing and cochlear hearing losses as a function of the stimulation level relative to the response threshold level (in dBRTL)

Stim. level	**Normal hearing**			**Cochlear hearing loss**		
dBRTL	**LI**	**LIII**	**LV**	**LI**	**LIII**	**LV**
100	0.06	0.05	0.08			
	n = 8	n = 9	n = 9			
90	0.07	0.05	0.09			
	n = 20	n = 20	n = 20			
80	0.09	0.05	0.06			
	n = 17	n = 19	n = 19	n = 1	n = 1	n = 1
70	0.10	0.06	0.07			
	n = 18	n = 19	n = 19	n = 2	n = 2	n = 2
60	0.08	0.06	0.08			
	n = 16	n = 20	n = 20	n = 2	n = 4	n = 4
50	0.09	0.11	0.10			
	n = 10	n = 18	n = 20	n = 3	n = 3	n = 3
40	0.11	0.15*	0.12*	0.10	0.08*	0.06*
	n = 5	n = 15	n = 20	n = 6	n = 7	n = 10
30		0.15	0.10			0.11
		n = 13	n = 20		n = 2	n = 7
20		0.17*	0.10		0.08*	0.11
		n = 11	n = 19		n = 7	n = 12
10			0.17			0.15
		n = 2	n = 20			n = 13
0			0.22			0.21
			n = 12			n = 14

$p < 0.05$: significant difference between the two groups. n = Number of ears.

As mentioned in the introduction. the horizontal shift of the l(L) curve is used for estimating the conductive hearing loss. When this is done. the inaccuracy of the latency measurements (in ms) must be transformed into an equivalent in the horizontal direction (in dB). In fig.1 the mean l(L) curve of peak V for the normal male reference group, consisting of 20 ears with normal hearing, is given together with the inaccuracies shown in table II and table III. By horizontal projection, the equivalent inaccuracy in the horizontal direction at each stimulation level was determined. The conversion of the corresponding female data was performed in the same way, using the female reference curve.

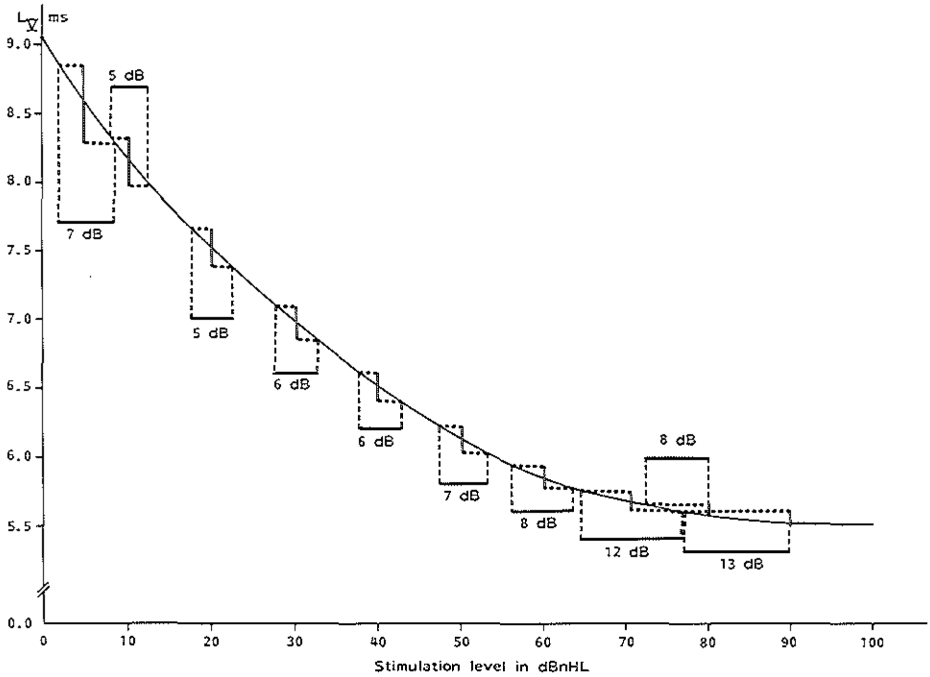

Fig. 1
Mean l(L) curve of peak V for male adults with normal hearing. At each stimulation level the inaccuracy of the measurement of the latencies of peak V is symbolized by a bold vertical line. Horizontal projection (horizontal dotted lines) of its end-points on the mean l(L) curve gives twice the equivalent inaccuracies in the stimulation level (solid horizontal lines). For the stimulation levels 80 and 90 dBnHL only the left projection was taken.

Figure 2 shows the inaccuracies in the horizontal direction (in dB) as a function of the mean normal latency of peak V in normal hearing, for both males and females. For latencies above 5.8 ms the inaccuracies appear to be less than 4 dB. For smaller latencies the inaccuracy sharply increases to about 13 dB at the mean peak V latency of 5.5 ms.

Thus because of the shape of the l(L) curve the most accurate peak V latencies, i.e. those smaller than 6 ms, make the largest contribution to the inaccuracy of the horizontal shift of the curve. Therefore it seems appropriate to disregard the latencies below 6 ms when estimating this shift.

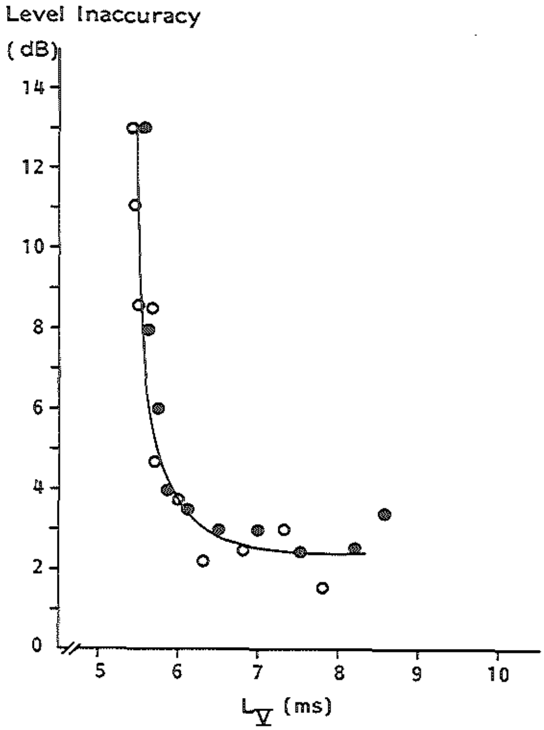

Fig. 2
The equivalent inaccuracies in measurement in the stimulation level direction (in dB) as a function of the latency of peak V. Open circles: female data. Closed circles: male data.

The present data do not allow a similar conversion for the group with cochlear hearing loss. However, as mentioned in the introduction, the use of the measurement inaccuracy is mainly meant for conductive hearing loss, in which the shape of the I(L) curve is supposed to be normal.

The data reported above on the intra-subject spread of the peak latencies suggest that one should consider the relation between the intra- and inter-subject variance. In the normal hearing group an analysis of variance of the peak V latency was performed to determine this relation. The latency data were corrected for gender differences (the correction in our population varied from about 0.1 ms for high stimulation levels to about 0.5 ms near the threshold), because from the literature it is apparent that there are considerable sex differences for peak III and V latencies (McClelland and McCrea (1979), Stockard et al.(1979), Jacobson et al.(1980), Jerger and Hall (1980), Debruyne et al.(1980), Patterson et al.(1981)). The results of the analysis are given in table V. As appears from the last 2 columns in this table, the intra-subject variance is significantly smaller than the inter-subject variance ($p<0.05$) at all stimulation levels.

Table V. Results of one-way analysis of variance for intra, versus interindividual variability of the latency of peak V as a function of the stimulation level in a population of 20 ears with normal hearing

Stim. level dBnHL	**Intra-individual SD**		**Inter-individual SD**		**Critical value ($p < 0.05$)**	**F value**
	mean value	**95 % confidence interval**	**mean value**	**95 % confidence interval**		
100	0.08	0.06-0.12	0.10	0.06-0.15	2.12	3.9
90	0.09	0.07-0.12	0.09	0.06-0.15	2.12	3.4
80	0.06	0.05-0.09	0.10	0.07-0.15	2.12	6.0
70	0.09	0.07-0.13	0.15	0.10-0.24	2.12	7.0
60	0.07	0.05-0.10	0.13	0.08-0.20	2.12	7.6
50	0.10	0.08-0.14	0.14	0.09-0.22	2.12	5.1
40	0.12	0.09-0.17	0.14	0.10-0.28	2.12	4.8
30	0.12	0.09-0.17	0.15	0.09-0.23	2.16	4.3
20	0.14	0.11-0.21	0.22	0.14-0.35	2.12	6.0
10	0.16	0.12-0.25	0.30	0.18-0.51	2.46	8.1

The ratio of the intra- and inter-individual mean standard deviations as a function of the stimulation level remains more or less unchanged. Comparison of the standard deviations shows that the intra- and inter-individual variabilities of the peak V latencies in subjects with normal hearing contribute about equally to the total variance at all stimulation levels.

The inaccuracy in the measurement of the auditory brainstem response threshold in normal hearing appears to be 3.8 dB. This figure is theoretically incorrect because of abnormal skewness of the underlying distribution. The inaccuracy of the response threshold in normal hearing is about equal to that measured for cochlear hearing loss (3.1 dB, chapter II). We feel that the abnormal skewness of the distribution can only have effected a slight increase on the figure.

According to the international standard (ISO 1983) the inaccuracies of the pure tone thresholds at 2 and 4 kHz are 2.8 and 3.7 dB respectively. These values are in the same range as those found by Witting and Hughson (1940): 3.9 and 4.2 dB for subjects with impaired hearing and 2.8 and 3.7 dB for those with normal hearing. Atherley and Dingwall-Fordyce (1963) found an inaccuracy of 2.7 dB at

3 kHz. Comparing these data it can be concluded that the inaccuracy in measuring the brainstem response threshold in normal hearing and cochlear impaired patients is about the same as that found when determining the subjective threshold for pure tones at 2 and 4 kHz.

Conclusions

1. The inaccuracy in measurement of the peak latencies in normal hearing is less than 0.1 ms at stimulation levels higher than 50 dBnHL. For lower stimulation levels it varies from slightly more than 0.1 ms to more than 0.2 ms near the threshold.

2. The latency-inaccuracy can be transformed into an inaccuracy of the latency-intensity curve in the intensity direction (in dB). For latencies larger than 6.0 ms this "horizontal" inaccuracy is less than 4 dB. For smaller latencies this figure rapidly increases up to 13 dB for a latency of 5.5 ms.

3. In normal hearing the intra- and inter-individual contributions to the total variance of the peak V latency are about equal at all stimulation levels.

4. The auditory brainstem response threshold is about as accurate a measurement of hearing sensitivity as the pure tone threshold. The accuracy of the response threshold is 3.8 dB in normal hearing and 3.1 dB in cochlear hearing loss.

References

Atherley G.R.C.. Dingwall-Fordyce I.
The reliability of repeated auditory threshold determination
Brit. J. Industr. Med. 1963. 20: 231-235

Debruyne F.. Hombergen G.. Hoekstra M.
Normal values in brainstem evoked potentials
Acta Otorhinolar. Belg. 1980. 34: 238-245

Edwards R.M.. Buchwald J.S.. Tanguay P.E.. Schwafel J.A.
Sources of variability in auditory brain stem evoked potential measures over time
Electroenceph. Clin. Neurophys. 1982. 53: 125-132

International Standard ISO 6189 . First edition 1983 -12-01

Jacobson J.T.. Novotny G.M.. Elliot S.
Clinical considerations in the interpretation of auditory brainstem response audiometry
Otolaryngol. 1980. 6: 493-504

Jerger J.. Hall J.
Effects of age and sex on auditory brainstem responses
Arch. Otolaryngol 1980. 106: 387-391

McClelland R.J.. McCrea R.S.
Intersubject Variability of the Auditory-Evoked Brain Stem Potentials
Audiology 1979. 18: 462-471

McGee T.J.. Clemis J.D.
Effects of conductive hearing loss on auditory brainstem responses
Ann. Otol. Laryngol. 1982. 91: 304-309

Patterson I.V.. Michalewski H.J.. Thompson L.W.
Age and sex differences in the human auditory brainstem responses
J. Geront. 1981. 36: 455-462

Rosenhammer H. J.. Lindstrom B.. Lundborg T.
On the use of click-evoked electric brainstem responses in audiological diagnosis
I. The variability of the normal response
Scand. Audiol. 1978. 7: 193-205

Stockard J. E., Stockard J. J., Westmoreland B. F., Corfits L.
B.A.E.R. Normal Variation as a Function of Stimulus and Subject Characteristics
Arch. Neurol. 1979. 36: 823-831

Thornton A.R.D.
Bilaterally recorded early acoustic responses
Scand. Audiol. 1975. 4: 173-181

Thornton A.R.D.
Statistical properties of surface-recorded electrocochleographic responses
Scand. Audiol. 1975. 4: 91-102

Witting E.G., Hughson W.
Inherent accuracy of a series of repeated clinical audiograms
Laryngoscope 1940. 50: 259-269

Chapter IV

Brainstem Response Audiometry:
I. Its use in distinguishing between conductive and cochlear hearing loss

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Abstract

The auditory brainstem response (ABR-) thresholds and the latency-Level curves. l(L) curves. for peak V were determined in 22 subjects with normal hearing. in 40 patients with conductive hearing loss and in 79 patients with cochlear hearing loss. The goal of this study was to investigate the potentials to distinguish between different types of hearing loss on the basis of these ABR-data. For this purpose the horizontal shift of the l(L) curve. the horizontal shift of its derivative and the latency of peak V at threshold level were plotted against the response threshold. For response thresholds above 30 dBnHL both the horizontal shift of the l(L) curve and the horizontal shift of its derivative give a good separation between cochlear and conductive hearing loss. The combination of the response threshold with the shift of the derivative of the l(L) curve gave a slightly better separation than that of the response threshold with the shift of the l(L) curve itself.

Résumé

Les seuils des potentiels évoqués du tronc cérébral et les courbes de latence et d'intensité du pic V sont determinées dans un groupe de 22 sujets normaux. dans un groupe de 40 de patients ayant une surdité de conduction et dans un group de 79 patients ayant une surdité de perception. Le but de cette investigation était d'explorer les potentialités pour la différenciation des les sortes diverses de la surdité par ces resultats des potentiels évoqués du tronc cérébral. Dans ce but le déplacement horizontal de la courbe de latence et d'intensité. le déplacement horizontal de cette courbe dérivé et la latence du pic V au seuil étaient placés contre le seuil. Pour seuil au-dessus de 30 dBnHL le courbe de latence et d'intensité et son courbe dérivé touts le deux rendent possible une belle différenciation des surdités de conductions et de perception. La combination du seuil avec la déplacement de la courbe dérivé rends une différenciation un peu plus belle que la combination du seuil avec la courbe de latence et d'intensité soi-même.

Introduction

One of the purposes of brainstem response audiometry is to assess the amount and nature of hearing loss in patients who cannot perform in the usual audiometric procedures. Two features are studied in brainstem response audiometry: the brainstem response threshold and the latencies of the peak V. It was shown that the auditory brainstem response threshold for click stimulation gives a good estimate of the amount of high-frequency hearing loss of cochlear origin (chapter II). The response threshold had a correlation coefficient of 0.93 with the average of the pure tone thresholds at 2 and 4 kHz. and the standard error of the estimate was found to be 11 dB.

Conductive hearing loss is frequently observed in the group of patients in which brainstem response audiometry is widely utilized. i.e. infants and children. Therefore a referring ENT surgeon will not only be interested in the threshold but also in the relative importance of cochlear and/or conductive components. In order to discriminate between these different types of hearing loss the latencies of peak V are often used. The latency of peak V is plotted against the stimulation level and will be referred to as the latency-Level curve (l(L) curve). According to the literature the form of this l(L) curve is different in different types of hearing loss. The following paragraph will focus on the relationship between pure tone audiogram and 3 main aspects of the curve: its shape and the horizontal and the vertical distances between the patient l(L) curve and the normal reference curve.

Assuming that a purely conductive hearing loss will result in a reduction of the level of effective stimulation of the cochlea. such a loss will shift the l(L) curve horizontally. while the shape of the curve will not change. In such cases the amount of the shift would be equal to the air-bone gap. As has been shown by Yamada et al.(1975). this gap can be measured along a horizontal line at threshold latency. Yamada et al.(1975) correctly predicted 80% of air bone gaps within 15 dB in a study of 12 ears. McGee and Clemis (1982) used an alternative method. They calculated the shift of the curve by taking the average of the horizontal shifts of all the data points on the curve. and predicted "almost all" air-bone gaps correctly within 10 dB in a study of 32 ears. Both Borg et al.(1981) and Fria and Sabo (1979) carried out studies of 10 ears and measured the horizontal shift in a way similar to Yamada. They described the relation between the horizontal l(L) shift and the air-bone gap in terms of a correlation coefficient of 0.84 and 0.81 respectively. Suzuki and Suzuki (1977) and Lehnhardt (1981) merely compared mean values of air-bone gaps and l(L) shifts. while Galambos and Hecox (1978) and Gerull et al.(1978) both showed one case. All studies mentioned above are only concerned with the effects of purely conductive hearing losses. Yet. although none of these studies primarily focussed on differentiation between cochlear and conductive hearing loss. they indicate the potential usefulness of the horizontal shift of the l(L) curve for this purpose.

Besides horizontal shift also vertical shift of the l(L) curve is reported in cases of cochlear hearing loss. The vertical shift of the curve. as calculated by Yamada et al.(1979). was shown to be related to both the audiogram shape and the amount of cochlear hearing loss. Lehnhardt (1981) pointed attention at vertical shift of the l(L) curve when the cochlear hearing loss exceeds 60 dB. This was demonstrated by comparing the reference curve with a curve based on the mean latency data of 10 patients. Coats (1978) analyzed 37 ears with high-frequency hearing losses of varying degree. and compared the audiograms with the corresponding l(L) curves. He found that the curves tended to shift vertically. The shift being proportional to the high-frequency loss. For instance at a constant stimulation level of 108 dBpeSPL. the mean latency of peak V increased from 5.8 ms to 6.4 ms when the high-frequency loss increased from 0 to 80 dB.

Apart from horizontal and vertical shifts. hearing loss can also cause changes in the shape of the l(L) curve. Yamada et al.(1979) described a steeper than normal l(L) curve for 7 patients who suffered from Ménières disease and had a flat or low-frequency hearing loss. Lehnhardt (1981) reported the mean of the l(L) curves of 19 patients with more than 55 dB cochlear hearing loss. His data also suggest that the l(L) curves are steeper than normal in the cases of cochlear hearing loss.

Coats (1978). Jerger and Mauldin (1978). and Sohmer et al.(1981) mentioned that an increase of the latency of peak V. measured at a fixed high stimulation level. was associated with an increase of high frequency hearing loss. Jerger and Mauldin found that the latency of peak V correlated better with the audiogram shape (steepness) than with high-frequency hearing loss.
Chisin et al.(1983) plotted a scatterdiagram of the response threshold against the vertical shift of the l(L) curve for 3 different groups: 9 patients with cochlear hearing loss. 19 with conductive hearing loss and 12 with mixed hearing losses. The figure shows a moderate degree of separation between the 3 sets of data. The authors concluded that a study of both the response threshold and the latency of peak I generally enables correct differential diagnosis between sensorineural. conductive or mixed hearing loss. However. part of the separation between the 3 groups can be attributed to non-overlapping threshold ranges for the groups. In our opinion no far-reaching conclusions can be drawn from these data.

In summary. the literature is ambiguous about the use of the l(L) curve as a tool for distinguishing between different types of hearing loss. Moreover. no information can be found about brainstem response audiometry as an instrument for estimating the relative contributions of the cochlear and conductive components in cases of mixed hearing loss.

From preliminary observations in patients we got the impression that the combination of the brainstem response threshold and 3 particular parameters of the l(L)-curve enables a better discrimination between cochlear and conductive hearing losses than the simple l(L) curve alone. These parameters are: the horizontal shift of the l(L) curve itself. the shift of its first derivative and the latency of peak V at threshold level (this will be referred to as the maximum peak V latency). The concept of the first derivative of the l(L) curve was inspired by our observation that in many cases of cochlear hearing loss the latency of peak V hardly increases when the stimulation level is reduced, even when the latency at high stimulation levels is already abnormally high. The first derivative can be especially useful for separating the vertical shift of the I(L) curve from the horizontal shift. The purpose of this study is to quantify the discriminative power of brainstem response audiometry between types of peripheral hearing loss as such. Of course the discriminative power can be enlarged by combination with other methods of examination, e.g. impedance audiometry and otoscopy.

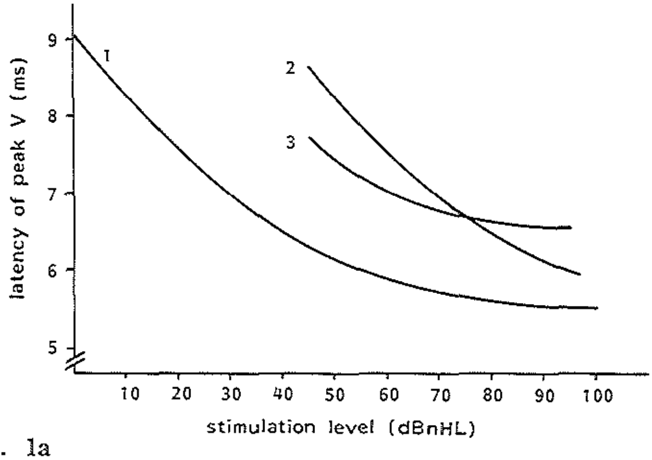

Fig. 1a

The reference I(L) curve (1), a horizontally-shifted "conductive" curve with the shape of the normal curve (2) and a "cochlear" curve with a flattened shape (3).

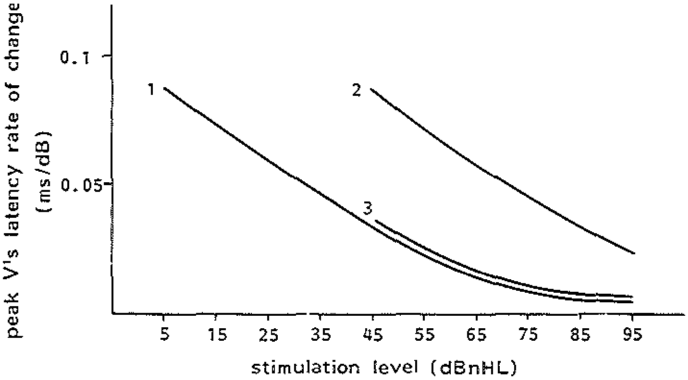

Fig. 1b

The first derivatives of the 3 curves shown in fig 1a. Note that the horizontal distance has not changed between curves 1 and 2 and has disappeared between the curves 1 and 3.

When simply computing the mean shift in the horizontal direction, as McGee and Clemis (1982) did, one must be aware of the additional effects that a vertical shift or a change in shape can have on the resulting figure; both can also appear as a horizontal shift. The horizontal shift of the first derivative of the I(L) curve gives a more accurate specification of the horizontal position of the curve. To illustrate this fig.1a shows the normal reference I(L) curve(1), a hypothetical, ideal "conductive type" curve(2), and a "vertically shifted" curve(3), as found incidentally for ears with cochlear hearing impairments. The response thresholds for both curves (2) and (3) are at 45 dBnHL. Determination of the horizontal shift according to McGee results in about equal values for both the shifted curves. However, the first derivatives, determined by taking the dI/dL-values for all levels, (fig.1b) show a different relation to the new reference curve. While the horizontal distance between the reference curve and the "conductive" curves remains unchanged, the separation between the reference and the "cochlear" curves has disappeared.

In this study we aim to answer to the following questions:

1. What is the value of the combination of the response threshold and the horizontal shift of the I(L) curves in distinguishing between cochlear and conductive hearing losses?

2. What is the value of the combination of the response threshold and the horizontal shift of the derivative I(L) curves in distinguishing between cochlear and conductive hearing losses?

3. What is the value of the combination of the response threshold and maximum peak V latency in distinguishing between cochlear and conductive hearing losses?

Procedures

Equipment and measurement procedures.

The equipment is described in detail in chapter II. (See table I of this chapter for summary.)
In the normal hearing group and in the group with conductive hearing losses, the initial stimulation level was always 100 dBnHL (in the above-mentioned, previous work stimulation was usually started at 90 dBnHL). Depending on the result, the stimulus level was increased or decreased in steps of 10 or 20 dB until the threshold level was approached. The threshold level was defined as the lowest stimulation level with a reproducible peak V in the response. The threshold level was determined in steps of 5 dB. All responses were assessed by two experienced observers [M.B., F.v.d.D.] who had no knowledge of the pure tone audiogram.

Table I. Summary of data on measurement technique

Click polarity	alternating
Click duration	100 μs
Click repetition frequency	20 Hz
Headphone	TDH-39
Electrode impedances	< 2 kΩ
Filter bandwidth	10-4000 Hz
Filter slopes	24dB/oct.
Number of runs	2048
Artifact rejection levels	-12.5 to $+12.5$ μV
Time resolution	29.3 μs

Data processing

To compute the horizontal shift of the I(L) curves in each case, the differences in the level direction between the individual points of the patients I(L) curve and the mean normal curve were measured and averaged (McGee and Clemis (1982)). The data for peak V latencies below 5.9 ms were not included in the calculations (chapter III). The derivative I(L) curves were approximated in a piecewise linear manner by taking the difference in the latencies of peak V per 10 dB difference in stimulation level. The horizontal shifts of these derivatives of the I(L) curves relative to the derivative of the reference curve were calculated in a similar way to the horizontal shifts of the I(L) curves.

Patient selection

To obtain normative data for I(L) curves, 12 male and 10 female subjects with normal hearing were tested. Hearing was considered to be normal if the mean of the pure tone air conduction thresholds did not exceed 7.5 dBHL and none of the thresholds exceeded 15 dBHL. The age of the subjects ranged from 20 to 40 years, with a mean of 27 years.

For a test group with cochlear hearing loss, patients were selected from the test population of a previous study (chapter II), according to the following criteria. The subjects had to be able to produce a reliable audiogram, containing both the air-conduction and bone-conduction thresholds at all usual frequencies. Retrocochlear pathology was excluded by the clinical history, ENT examination and neurological examination (in this study limited to the examination of the cranial nerves). In case of any suspicion of retrocochlear pathology, stapedial reflex tests, electronystagmography and sometimes CT scanning were used to enable further selection. If the results were inconclusive, the patient was excluded from the test group. Only patients whose audiogram showed a mean air-bone gap less then 7.5 dB and no air-bone gap exceeding 10 dB at any frequency were included. Apart from excluding retrocochlear pathology and conductive hearing loss. no selection was made on etiology. The etiologies of the hearing impairments involved in the test group were presbyacusis. Ménières disease. hereditary cochlear hearing loss. ototoxic medication and acoustic trauma. For some patients with cochlear hearing losses there was no known etiology. In this way 36 male and 43 female patients with a cochlear hearing loss were selected. Their ages varied from 10 to 85 years. with a mean of 45 years.

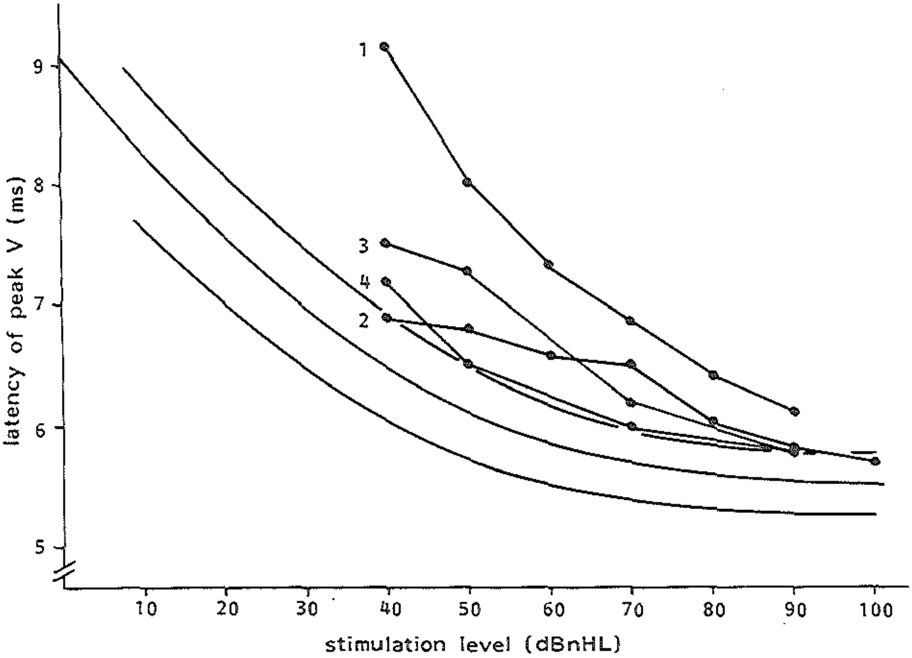

Fig. 2a

Reference l(L)-curve and 4 l(L) curves for ears with a brainstem response threshold of 40 dBnHL. Curve 1 and 2: conductive hearing losses. Curves 3 and 4: cochlear hearing losses.

Young adult patients with purely conductive hearing losses were submitted to pure tone audiometry and brainstem response audiometry on the same day. The etiology of the conductive loss was not used as a criterion for the selection and so all kinds of middle ear pathology (e.g. OME. perforation of the ear drum with and without suppuration. cholesteatoma and radical or modified radical mastoidectomy) were represented in the test group. A pure tone audiogram was classified as "purely conductive" when the mean of the bone-conduction thresholds at all usual frequencies did not exceed 10 dBHL and none of the bone-conduction thresholds exceeded 20 dBHL. The minimum air-bone gap for 0.5 to 4 kHz was 15 dB. The test group thus formed consisted of 23 male and 17 female patients varying in age from 10 to 45 years with a mean of 24 years.

Results

Figure 2a gives 4 examples of l(L)-curves, two representing ears with cochlear hearing losses and two with conductive hearing losses, all having a brainstem response threshold of 40 dBnHL. As a reference the l(L) curve for male subjects in our clinic with normal hearing is depicted, together with its 95% confidence limits. The etiologies of the 4 hearing losses of which the audiograms are shown in fig.2b are radical mastoidectomy(1), cholesteatoma(2), presbyacusis(3) and Ménières disease(4).

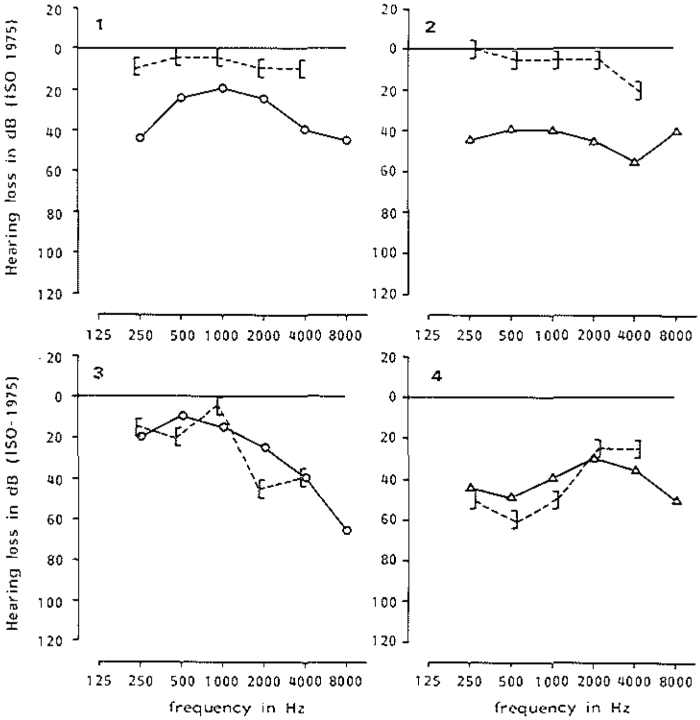

fig. 2b
Audiograms of the 4 cases presented in fig.2a.

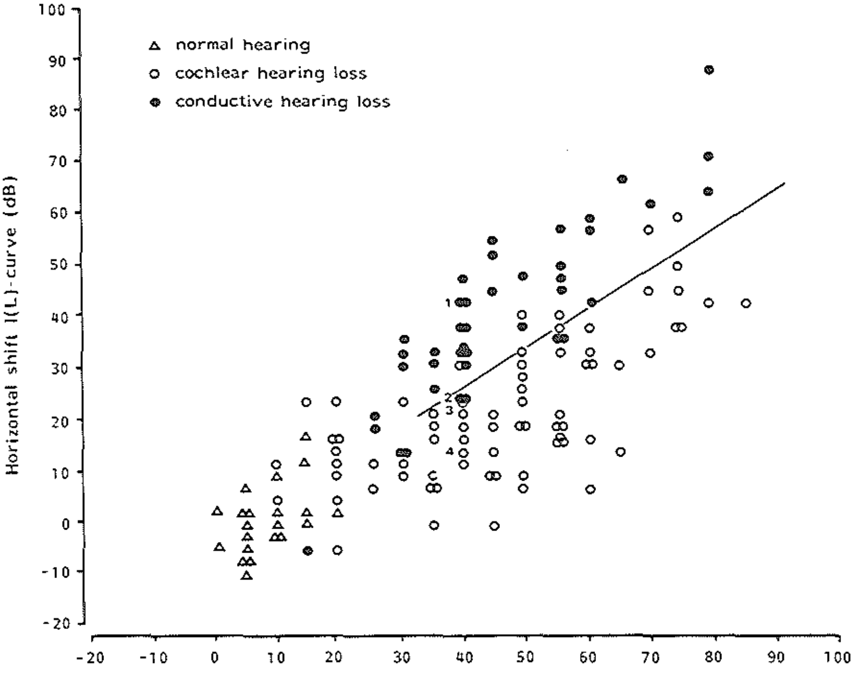

Fig. 3

The horizontal shift of the l(L) curve (in dB) as a function of the brainstem response threshold for normal hearing, cochlear hearing loss and conductive hearing loss. The numbers 1, 2, 3 and 4 represent the 4 cases shown in fig.2. The line is fitted by eye to separate cochlear and conductive data.

Figure 3 shows the horizontal shift of the l(L) curve (in dB) as a function of the auditory brainstem response threshold (in dBnHL) for normal hearing (open triangles), cochlear hearing loss (open circles), and conductive hearing loss (dots). The data for the group with cochlear hearing loss show considerable scatter and the horizontal shift tends to increase with a higher auditory brainstem response threshold. The data for the group with conductive loss show a linear relationship between the l(L) shift and the response threshold. This relation can be described using regression analysis, which gives a correlation coefficient of 0.88, a regression line with a slope of 0.95, and a standard error of the estimate of 8.5 dB (the lines in the figs.3 to 5 are used to mark the separation between the groups with cochlear and conductive hearing loss and will be discussed later). For response thresholds above 30 dBnHL the data sets for both groups seem to be well separated, showing only a narrow band of overlap. For response thresholds below 30 dBnHL there is no clear separation.

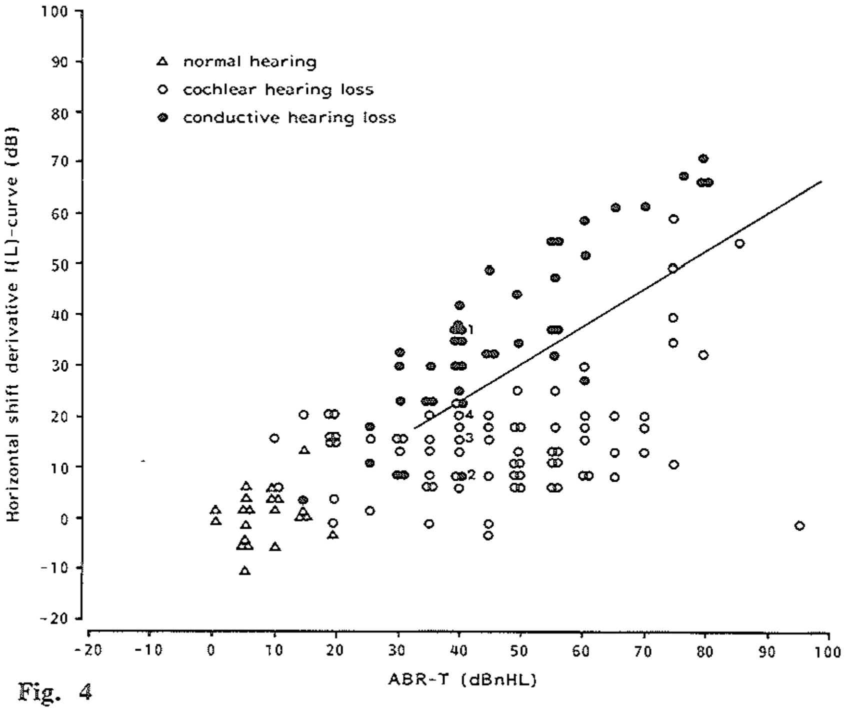

Fig. 4

The horizontal shift of the derivative I(L) curve as a function of the brainstem response threshold for normal hearing, cochlear hearing loss and conductive hearing loss. The numbers 1, 2, 3 and 4 represent the 4 cases shown in fig.2. The line is fitted by eye to separate cochlear and conductive data.

In fig.4 the horizontal shift of the first derivative of the I(L) curves is shown as a function of the response threshold for normal hearing, cochlear hearing loss and conductive hearing loss. The data for the group with cochlear hearing loss are less affected by the response threshold than in fig.3, while the data for conductive hearing loss appear to be quite similar to those in fig.3 ($r=0.89$; slope of the regression line=0.97; st.error of the estimate=8.2 dB)

Figure 5 shows the latency of peak V at threshold level as a function of the threshold, for normal hearing, cochlear hearing loss and conductive hearing loss. The maximum peak V latency in conductive hearing loss is in the normal range and independent of the response threshold. In cochlear hearing loss there is a significant negative correlation ($r=-0.37$; $p<0.05$) and the slope of the regression line is -0.2 ms/10 dB. The higher the response threshold the lower the latency of peak V at the threshold level appears to be.

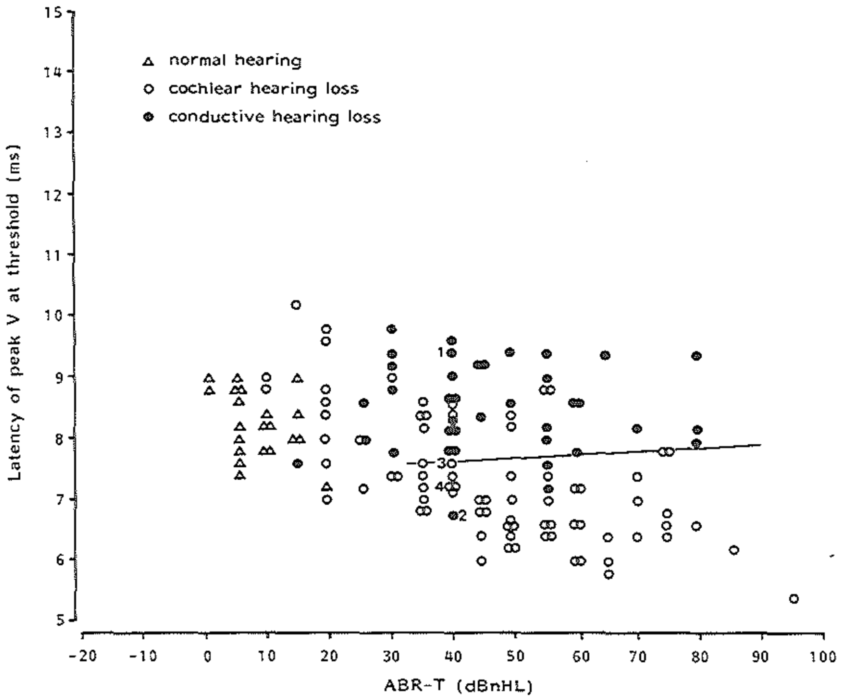

Fig. 5

The latency of peak V at threshold level as a function of the brainstem response threshold for normal hearing loss, cochlear hearing loss and conductive hearing loss. The numbers 1, 2, 3 and 4 represent the 4 cases shown in fig.2. The line is fitted by eye to separate cochlear and conductive data.

Discussion

In the scatter plots in figs.3 to 5 the sets of data for the two types of hearing loss show a considerable overlap for response thresholds below 35 dBnHL. Though the number of conductive hearing losses in this region is small in the present material. the scatter of the cochlear data suggests that brainstem response data are of no use for distinguishing between cochlear and conductive hearing loss for ears with response thresholds below 35 dBnHL. Of course. the smaller the hearing loss. the less important this distinction.

In our material the l(L) curve shows both the typical and the atypical behaviour (fig.2). In case 1. a typical example of conductive hearing loss. the curve displays a strong horizontal shift but the shape of the curve is quite similar to the normal one. In figs.3 to 5 this case can be regarded as a good example of this type of hearing loss: both the shift of the curve and the shift of the derivative curve are of about the same magnitude as the elevation of the response threshold. and the latency of peak V at threshold level is about the same as in the group with normal hearing. In all 3 scatter plots the data point for this case of conductive hearing loss is well separated from data for the ears with cochlear hearing loss. as is to be expected on theoretical grounds. In strong contrast to this is case 4. a typical example of cochlear hearing loss. This l(L) curve is approximately normal except that the part for the lower levels is missing. In the scatter plots the data point for this ear is separated from the main group of data representing ears with conductive hearing loss. The cases 2 and 3 illustrate the other side of the coin: although their tone audiograms emphasize the very different types of hearing loss. the l(L) curves are quite similar. In the scatter plots they are used as examples to demonstrate that distinction between the different types of hearing loss is not completely reliable on the basis of brainstem response data alone.

In the 3 scatter diagrams the sets of data for the cochlear and conductive hearing losses are situated near each other and show some overlap. For response thresholds above 30 dBnHL the drawn lines in figs.3 to 5 were fitted by eye and give the optimum separation between the 2 groups. Of the 34 cases of conductive hearing loss with response thresholds above 30 dBnHL. 4 are misclassified in figs.3 and 4. and 3 are misclassified in fig.5. Of the 58 cochlear hearing losses 5 are misclassified in fig.3. 3 in fig.4 and 7 in fig.5. The clearest separation between the 2 groups is found in fig.4. where the shift of the derivative curve is plotted against the response threshold. The overlap between the cochlear and conductive group will cause some problems when mixed hearing losses also have to be distinguished as a separate group. From the results it can be concluded that for response thresholds above 30 dBnHL the combination of on the one hand the response threshold and on the other hand the horizontal shift of the l(L) curve. the shift of the derivative l(L) curve and the maximum peak V latency can be used for distinguishing graphically between cochlear and conductive hearing losses. A quantitative method for investigating the value of the brainstem response data for distinguishing between different categories of hearing loss is provided by discriminant analysis. The contribution of this method will be discussed in chapter V.

Conclusions

1. For response thresholds above 30 dBnHL the combination of on the one hand the response threshold and on the other hand the horizontal shift of the l(L) curve. the shift of the derivative l(L) curve or the maximum peak V latency can be used for distinguishing graphically between cochlear and conductive hearing losses.

2. In conductive hearing loss the latency of peak V at the response threshold is independent of the level of the response threshold. In cochlear hearing loss the latency of peak V at the response threshold level decreases with increasing response threshold.

3. For ears with response thresholds above 30 dBnHL the combination of the response threshold and the horizontal shift of the derivative of the l(L) curve provides a slightly more accurate instrument for distinguishing between cochlear and conductive hearing loss than the combination of the response threshold and the horizontal shift of the curve itself.

References

Borg E.. Lofqvist L.. Rosen S.
Brainstem responses in conductive hearing loss
Scand. Audiol. 1981. 13 suppl.: 95-97

Chisin M.. Gafni M.. Sohmer H.
Patterns of auditory nerve and brainstem evoked responses in different types of peripheral hearing loss
Arch. Otorhinolar. 1983. 237: 165-173

Coats A.C.
Human auditory responses
Arch. Otolaryng. 1978. 104: 709-717

Fria T.J.. Sabo D.L.
Auditory brainstem responses in children with otitis media with effusion
Ann. Otol. Rhinol. Laryngol. 1979. 89/3 II suppl.68: 200-206

Galambos R.. Hecox K.
Clinical applications of the auditory brain stem response
Otolar. Clin. N A 1978. 11: 709-721

Gerull G.. Giesen M.. Mrowinski D.
Quantitative Aussagen der Hirnstammaudiometrie bei Mittelohr- kochlearen und retro-kochlearen Horschaden
Laryng. Rhinol. 1978. 57: 54-62

Jerger J.. Mauldin L.
Prediction of sensorineural hearing level from the brainstem response
Arch. Otolaryngol. 1978. 104: 456-461

Lehnhardt E.
The sound intensity-related behaviour of the brain stem response P6 in different forms of hearing disorders
Ann. Otol. Rhinol. Lar. 1981. 91: 304-309

McGee T.J.. Clemis J.D.
Effects of conductive hearing loss on the auditory brainstem response Ann Otol Rhinol. Lar. 1982. 91: 304-309

Sohmer H.. Kinarti R.. Gafni M.
The Latency of Auditory Nerve-Brainstem Responses in Sensorineural Hearing Loss
Arch. Otolaryngol. 1981. 230: 189-199

Suzuki M.. Suzuki J.I.
Clinical application of the auditory evoked brain stem response in children
A.N.L. 1977. 4: 19-26

Yamada O.. Yagi T.. Yamane H.. Suzuki J.I.
Clinical evaluation of the auditory evoked brain stem response
A.N.L. 1975. 2: 97-105

Yamada O.. Kodera K.. Yagi T.
Cochlear processes affecting wave V latency of the auditory evoked brain stem response
Scand. Audiol 1979. 8: 67-70

Chapter V

Brainstem Response Audiometry:
II. Assessment of the type of hearing loss using discriminant analysis

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Abstract

In chapter IV it was shown graphically that conductive and cochlear hearing loss can be distinguished on the basis of the combinations of the auditory brainstem response threshold with the horizontal shift of peak V's latency-Level curve. its derivative or the latency of peak V at threshold level. respectively. In addition to the patient data used in chapter IV. for the present study 22 patients with mixed hearing loss were included. The statistical technique of discriminant analysis was applied to find the optimum linear combination of ABR-data for classification of a hearing loss. The brainstem classification "cochlear hearing loss" agrees with the diagnosis on the basis of the pure tone audiogram in 85% of the cases. In cases with the brainstem classification "conductive hearing loss". 93% showed at least a conductive component in the pure tone audiogram.

Résumé

Dans une chapitre IV il etait démontré qu'il est possible de séparer graphiquement les surdités de conduction et de perception par les combinations du seuil de potentiels évoqués du tronc cérébral avec le déplacement horizontal de la courbe de latence et d'intensité du pic V. avec le déeplacement horizontal de cette courbe dérivé ou avec la latence du pic V au seuil. Supplémentaire aux résultats des potentiels évoqués. quels etaient utilisés dans la chapitre IV. 22 patients avec une surdité mixte ont été examiné. La methode statistique d'analyse discriminante etait appliqué pour determiner la combination linéaire des résultats des potentiels evoqués quelle est optimale pour classer d'une surdité. La classification 'surdité de perception' par la combination optimale s'accords avec la classification par l'audiogramme dans 85% des patients. Dans la classification 'surdité de conduction' par la combination optimale des résultats des potentiel évoqués l'audiogramme montrait un component de conduction dans la surdité en 93% des patient.

Introduction

The objective of chapter IV was to find the best way to classify the type and amount of hearing loss using brainstem response data. For this purpose the latency-Level curve (l(L) curve) was used. In the literature (Borg et al.(1981). Chisin et al.(1983). Lehnhardt (1981). Fria and Sabo (1979). McGee and Clemis (1982). Suzuki and Suzuki (1977). Yamada et al.(1979)) a relationship has been demonstrated between the purely conductive hearing loss. as estimated using the brainstem response l(L) curve and the air-bone gap in the tone audiogram. However. the value of the l(L) curve for identifying the type of hearing loss was not yet clear from the literature. due to insufficient numbers of patients and the use of different parameters which cannot easily be compared.

Three parameters of the l(L) curve can be used in combination with the auditory brainstem response threshold to distinguish between cochlear hearing loss and conductive hearing loss (chapter IV). These parameters are the horizontal shift of the l(L) curve, the horizontal shift of the first derivative of the curve and the latency of peak V at threshold level. It was concluded in chapter IV that certain combinations of these parameters and the brainstem response threshold give a certain degree of separation of the two types of hearing loss for response thresholds above 30 dBnHL. However, it was not possible to detect mixed hearing losses with the two-dimensional method described, because of the overlap between the cochlear and conductive data. The objective of this part of the study is to examine whether linear combinations of more than 2 parameters of the l(L) curve enable a better distinction to be made between different types of hearing loss, and in particular, whether mixed hearing loss can be distinguished from cochlear or conductive hearing loss.

The problems that need to be solved with the help of discriminant analysis are summarized in the following questions:

1. What is the optimum linear combination of parameters of the l(L) curve for distinguishing between cochlear, mixed and conductive hearing losses?

2. How reliable is this discrimination technique?

Discriminant analysis

The possibilities and limitations of discriminant analysis in medical diagnosis have been described by Brown (1984). The basic method is summarized in the present paper.

Discriminant analysis is a statistical method of classification in which the rules and categories for classification are based on data from groups of patients who have already been classified by an "extrinsic" procedure. In our study this extrinsic procedure is the pure tone audiogram. The method can be divided into an analysis phase and an evaluation or classification phase. As was shown in the scatter diagrams in chapter IV, pairs of parameters can be used in a two-dimensional plane to define the areas that represent the different groups of ears, these ears already having been classified by the "extrinsic" procedure of the study. This can be considered as a kind of graphical two-dimensional analysis and classification combined. Discriminant analysis determines in its analysis phase the combination of parameters (4 in our study) which gives the best separation between the different groups in the population (i.e. in our study: cochlear, conductive or mixed hearing loss). The analysis phase being completed, the second step -classification-can be carried out when the data point of an ear with an unknown type of hearing loss is placed in such a diagram and its type of hearing loss is estimated from its location: if it is located in an area topically representative for a specific group, the ear is classified as belonging to that group. With discriminant analysis the analysis phase provides computational rules that enable quantitative classification in a multi-dimensional space, i.e. using more than two parameters at a time.

Criteria for "extrinsic" classification

The criteria that were used to classify the ears according to the tone audiogram as normal or as having a cochlear, a conductive or a mixed hearing loss, are summarized in table I. The test population included the 3 groups that were described in chapter IV: 22 subjects with normal hearing, 79 patients with cochlear impairment and 40 patients with conductive hearing loss. To this test population a group of 22 patients with mixed hearing loss was added. Hearing loss was considered to be "mixed" when the mean of the pure tone air conduction thresholds exceeded 15 dBHL and when the mean air-bone gap exceeded 7.5 dB. The age of the subjects in this test group varied from 10 to 85 years, with a mean of 34 years. Only data of one ear per subject were used.

Table I. Selection criteria for the 'extrinsic' classification of cochlear conductive, and mixed hearing loss using the tone audiogram.

cochlear	mean air-bone gap < 7.5 dB
	no air-bone gap > 10 dB
conductive	mean bone conduction threshold < 15 dB
	no bone conduction threshold > 20 dB
mixed	air conduction threshold > 15 dB
	mean air-bone gap ⩾ 7.5 dB

Equipment and procedures

A complete description of the equipment and measurement methods is given in chapter IV.

Data processing

The data for the horizontal shifts of the l(L) curves and for their first derivatives were obtained in chapter IV. The standard procedure in the SPSS-X computer program was used for the linear discriminant analysis. As a first step determination of the best combination of parameters was carried out by discriminant analysis for all ears. For reasons of statistical correctness the final classification phase was done by the "leaving-one-out method" (Lachenbruch (1975)). This implies that each ear was classified using discrimination functions based on all other ears.

Table II. Percentage of correctly classified ears with both purely cochlear and purely conductive hearing loss together, as a function of various combinations of the 4 parameters of the l(L) curve. ABR-T: response threshold; l(L)-shift: horizontal shift of the l(L) curve; l'(L)-shift: horizontal shift of the first derivative of the l(L)-curve; lV_T: maximum peak V's latency.

ABR-T - l(L)-shift	87
ABR-T - l'(L)-shift	91
ABR-T - lV_T	86
ABR-T - l(L)-shift - l'(L)-shift	94
ABR-T - l(L)-shift - lV_T	86
ABR-T - l'(L)-shift - lV_T	91
ABR-T - l(L)-shift - l'(L)-shift - lV_T	94

Results

The potentials for discrimination were investigated for ears with response thresholds of 35 dBnHL and higher, for the reasons stated in chapter IV. For this subset of the population, table II gives data on the capacity to separate the groups that are "extrinsically" classified by the tone audiogram as belonging to the purely-cochlear or purely-conductive type. The percentages of ears with cochlear or conductive hearing loss that were thus classified by means of the brainstem response data are given as a function of the combinations of the response threshold (ABR-T), the horizontal shift of the l(L) curve (l(L)-shift), the horizontal shift of the first derivative of the l(L) curve (l'(L)-shift) and the latency of peak V at threshold level (l-Vt). The best overall agreement between the classifications based on the brainstem response data, on the one hand, and the pure

tone audiogram on the other hand was 94%. This was found for the combination of the response threshold and the shifts of both the l(L)-curve itself and its derivative. The table also shows that adding the latency of peak V at threshold level does not improve the classifications.
The reference data for the peak V latency for male and female subjects in this study are given in Appendix A.

Having determined that combination of parameters of the l(L) curve that gives the best discrimination, this combination was used to classify the ears with response thresholds above 30 dBnHL as having cochlear, mixed or conductive hearing loss. The parameters of these classification functions are given in Appendix B.
The classification phase was repeated, but now by the "leaving-one-out method", as described in the section on data processing. The results are given in table III. The percentages are corrected for the numbers of ears in different groups. In this table the data for the ears that are classified by brainstem response data as suffering from cochlear, conductive or mixed hearing loss are broken down by "extrinsic classification". Thus, for instance, if according to the brainstem response data a patient suffers cochlear hearing loss (first column), in 86% of the cases this is in agreement with the "extrinsic" classification by the tone audiogram criteria. 3% of these ears were classified by the tone audiogram as having conductive and 11% as mixed hearing loss.

Table III. Cross-classification table, giving cochlear, conductive and mixed hearing loss obtained from brainstem response data (response thresholds above 30 dBnHL) and discriminant analysis against the 'extrinsic' classification using the tone audiogram. The figures have been corrected to allow for differences in the numbers involved in of the three categories of hearing loss. (...): number of ears.

ABR+discrim. anal.	**tone audiogram**			
	cochlear	**conductive**	**mixed**	**total**
cochlear	86 % (51)	3 % (1)	11 % (2)	100 %
conductive	0 % (0)	68 % (25)	32 % (6)	100 %
mixed	14 % (7)	25 % (7)	61 % (9)	100 %

Discussion

With the help of linear discriminant analysis it appears to be possible to combine various parameters of the I(L) curve in a multi-dimensional space for distinguishing between different types of hearing loss. The analysis phase enables a simple classification formula to be compiled as described in Appendix A. Thus the processes involved from the determination of the peak V latencies to the classification of the type of hearing loss, can be automated and the reliability of the results can be quantified. We consider this a welcome supplement in the clinical use of brainstem response audiometry.

Table III shows the impact on the clinical practice of this calculation. In the first row 86% of the ears that were classified by the brainstem response data as having cochlear hearing loss were placed in the same category using the tone audiogram criteria. In another 11% the tone audiogram showed at least a cochlear component in the hearing loss, and in only 3% was there no agreement at all between the two measurements. This means that when brainstem response data indicate that a patient has cochlear hearing loss, further therapy and guidance appropriate to this handicap should take place without delay. The second row in the table shows that when according to the brainstem data the hearing loss is of the purely conductive type, purely cochlear impairments can be excluded. However, in 32% of the cases the tone audiogram shows a cochlear component in the hearing loss. Thus the brainstem diagnosis "conductive hearing loss" always means that there is at least a conductive component in the hearing loss. Those cases in which there was no agreement between the intrinsic and extrinsic classifications were all reviewed separately. No specific common aspect was found in the pure tone audiogram that might be associated with the misclassifications. However, no proper statistical investigation on this matter could be done due to insufficient numbers.

Because 32% of the cochlear components were missed, a second measurement after treatment of the conductive hearing loss is the logical next step. When the brainstem data classify a hearing loss as "mixed", in 14% of the cases therapy for the conductive component in the hearing loss will be unnecessary, causing an undesirable delay in starting the treatment for cochlear hearing loss.

In principle, for optimum results one of the conditions for the application of linear discriminant analysis is that covariance matrices should be equal. Box's M-test showed that for the present data the covariance matrices were significantly different (p:0.0001). Strictly speaking, this indicates that a logistic discriminant analysis is preferable to a linear one. However, the inequality of the covariance matrices can at least partly be explained by the "cut-off effect", caused by leaving out the ears with response thresholds below 35 dBnHL. Moreover. Schmitz et al.(1983. 1985) have demonstrated that for numerical variables the linear discriminant analysis is nearly as robust as the logistic one. Therefore. for the sake of simplicity and clinical applicability we choose the linear discriminant analysis. the more so as the resulting discrimination appears to be quite satisfactory.

In these interpretations of the presented data it is important to keep in mind that such figures are influenced by the prevalence of the different types of hearing impairment in the population to be measured. The results shown in table III. from the standard procedure discriminant analysis (SPSS-X). are only correct for equal prevalences. However. Kankkunen (1982) for instance. estimated the prevalence of conductive hearing loss for infants in the Swedish population to be 50 times higher than that of cochlear hearing loss. The reports on the ratio of these prevalences in the Netherlands are not consistent and moreover. an unknown. probably large proportion of patients with conductive hearing losses will never be submitted to brainstem response audiometry because the ENT surgeon will already have treated them successfully. In the authors' clinical setting the ratio of patients that were diagnosed by brainstem response data as having cochlear. conductive or mixed hearing loss was until now 1:3:1. To use this ratio in further calculations is of course statistically questionable. but we consider that in our clinic it gives a reasonable approximation to the unknown reality.

Table IV. Cross-classification table. giving cochlear, conductive and mixed hearing loss obtained from brainstem response data (response thresholds above 30 dBnHL) and discriminant analysis against the 'extrinsic' classification using the tone audiogram. The figures have been corrected for differences in the numbers involved in the three categories of hearing loss. The prevalence-ratio used for cochlear, conductive and mixed hearing loss is 1: 3: 1. (...): number of ears.

ABR+discrim. anal.	**tone audiogram**			
	cochlear	**conductive**	**mixed**	**total**
cochlear	85 % (49)	3 % (1)	12 % (2)	100 %
conductive	7 % (7)	52 % (31)	41 % (13)	100 %
mixed	19 % (2)	16 % (1)	65 % (2)	100 %

The results of discriminant analysis corrected for the above mentioned prevalence ratio are shown in table IV. The agreement between the diagnoses based on brainstem response data and the tone audiogram becomes slightly less favourable for the class "cochlear hearing loss". The brainstem diagnosis "conductive hearing loss" should have been "cochlear" according to the tone audiogram in 7% of cases. In the remaining 93% it correctly determines the existence of a conductive hearing loss. though in about half of that group a cochlear component is missed. The brainstem diagnosis "mixed hearing loss" now correctly indicates a conductive hearing loss component in 81% of cases. but in 16% the suggested cochlear component was not evident in the pure tone audiogram. Thus it appears that the reliability of the method (as is. of course. true for all clinical tests) is influenced by the prevalences of the types of hearing loss to be detected. However. a more realistic prevalence ratio does not affect the reliability of the prediction of a cochlear hearing loss. while the existence of a conductive hearing loss is still correctly determined in most cases. Thus it is still not possible to make a clear distinction between mixed and conductive hearing loss.

The aim of this study was to determine the value of air-conducted brainstem response audiometry for the classification of different types of hearing loss. As has been demonstrated before. in some cases the classification is not completely reliable. In cases with response thresholds below 35 dBnHL. and in some cases when the brainstem diagnosis is "conductive" or "mixed hearing loss". welcome additional information might be obtained with the help of bone conducted stimuli. Though the practical value of this instrument in brainstem response audiometry has been questioned (Kavanagh and Beardsley (1979)). several authors have described its merits (Hooks and Weber (1984). Hofmann and Flach (1981). Mauldin and Jerger (1979)). Especially the Cancellation method (Boezeman et al.(1985)). and the "Derived bone conduction threshold". (Hicks (1980)) were described to be promising.

Conclusions:

1. Linear discriminant analysis. applied to the combination of the brainstem response threshold. the horizontal I(L) shift and the horizontal shift of the derivative I(L) curve. is a useful instrument for the classification of different types of peripheral hearing loss.

2. For hearing losses with response thresholds above 30 dBnHL the brainstem classification "cochlear hearing loss" is in good agreement with the diagnosis obtained using the pure tone audiogram.

3. For hearing losses with response thresholds above 30 dBnHL the brainstem classifications "conductive hearing loss" and "mixed hearing loss" are in good agreement with the existence of a conductive component in the pure tone audiogram.

Appendix A

Means and standard deviations of peak V latencies in normal hearing for male and female subjects.

Stim. level dBnHL	Male N	 mean	 st. dev.	Female N	 mean	 st. dev.
100	20	5.51	0.16	19	5.43	0.12
90	20	5.54	0.14	19	5.45	0.09
80	20	5.62	0.13	18	5.51	0.12
70	20	5.75	0.15	18	5.67	0.15
60	20	5.85	0.16	19	5.73	0.13
50	20	6.13	0.19	19	5.99	0.20
40	20	6.50	0.23	19	6.32	0.27
30	20	6.97	0.22	19	6.80	0.35
20	20	7.53	0.31	19	7.29	0.41
10	14	8.21	0.19	17	7.81	0.41
0	5	9.04	0.11			

Appendix B

The linear classification function used is represented by the formula:

$$Y_{lin} = b_0 + b_1X_1 + b_2X_2 + ... + b_nX_n$$

Y_{lin} is the classification score; b_0 is a constant provided by the analysis; b_1, b_2 etc. are the classification coefficients provided by the analysis and are used for weighing the predictor variables X_1, X_2 etc.. In this study X_1 etc. represent the brainstem data from which the classification has to be made: the horizontal shift of the I(L) curve, the shift of the derivative of this curve, the response threshold and the peak V's latency at threshold level. The classification functions are derived from the discrimination functions, using a prevalence ratio of 1:3:1 for cochlear, conductive and mixed hearing loss, respectively. The classification functions estimate the classification score that a hearing loss is of cochlear, conductive or mixed type. The type of hearing loss with the highest classification score should be chosen. For our material the classification functions are:

Cs(cochlear) = 0.391(ABR-T) - 0.160(I(L)-shift) - 0.041(I'(L)-shift) - 9.874

Cs(conductive) = 0.149(ABR-T) + 0.040(I(L)-shift) + 0.113(I'(L)-shift) - 7.582

Cs(mixed) = 0.227(ABR-T) - 0.010(I(L)-shift) + 0.056(I'(L)-shift) - 9.269

References

Boezeman E.H.J.F., Kapteyn T.S., Feenstra L., Snel A.M.
Verification of the air-bone gap using cancellation and evoked responses
Audiology 1985. 24: 174-158

Borg E., Lofqvist L., Rosen S.
Brainstem response (ABR) in conductive hearing loss
Scand. Audiol. 1981. suppl. 13: 95-97

Brown G.W.
Discriminant Analysis
AJDC. 1984. 138: 395-400

Chisin M., Gafni M., Sohmer H.
Patterns of auditory nerve and brainstem evoked responses in different types of peripheral hearing loss
Arch. Otorhinolar. 1983. 237: 165-173

Fria T.J., Sabo D.L.
Auditory brainstem responses in children with otitis media with effusion
Ann. Otol. Rhinol. Laryngol. 1980. 89/3 II suppl. 68: 200-206

Hicks G.E.
Auditory brainstem response. sensory assessment by bone conduction masking
Arch. Otolaryngol. 1980. 106: 392-395

Hofmann G., Flach M.
Hirnstammaudiomtrie bei akustischer Reizung uber Knochen- und Luftleitung
Laryng.-Rhinol. 1981. 60: 264-267

Hooks R.G., Weber B.A
Auditory brain stem responses of premature infants to bone conduction stimuli: a feasibility study
Ear and Hearing 1984. 5: 42-46

Kankkunen A.
Preschool children with impaired hearing
Acta Oto-Laryngol. 1982. suppl., 391

Kavanagh K.T.. Beardsley J.V.
Brain stem auditory evoked response III. Clinical use of bone conduction in the evaluation of otologic disease
Ann.Otol. Rhinol. Laryngol. 1979. Suppl. 58: 22-28

Lachenbruch P.A.
Discriminant Analysis
New York. Hafner Press 1975

Lehnhardt E.
The sound intensity-related behaviour of the brain stem response P6 in different forms of hearing disorders
Ann. Otol. Rhinol. Laryngol. 1981. 91: 304-309

Mauldin L.. Jerger J.
Auditory brain stem evoked responses to bone-conducted signals
Arch Otolaryngol. 1979. 105: 656-661

McGee T.J.. Clemis J.D.
Effects of conductive hearing loss on the auditory brainstem response
Ann. Otol. Rhinol. Laryngol. 1982. 91: 304-309

Schmitz P.I.M.. Habbema J.D.F.. Hermans J.. Raatgever J.W.
Comparative perfomance of four discriminant analysis methods for mixtures of continuous and discrete varables
Comm. stat.- Sim. comp. 1983. 12: 727-751

Schmitz P.I.M.. Habbema J.D.F.. Hermans J.
A simulation study of the performance of five discriminant analysis methods for mixtures of continuous and binominal variables
J. Stat. Comput. Sim. 1985. 23: 69-95

SPSS Inc.
SPSS-X Users Guide
McGraw-Hill Book Company. New York. U.S.A.

Suzuki M.. Suzuki J.I.
Clinical application of the auditory evoked brain stem response in children
A.N.L. 1977. 4: 19-26

Yamada O.. Yagi T.. Yamane H.. Suzuki J.I.
Clinical evaluation of the auditory evoked brain stem response
A.N.L. 1975. 2: 97-105

Chapter VI

Brainstem electric response audiometry: Estimation of the amount of conductive hearing loss with and without use of the response threshold

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Abstract

Three aspects of brainstem response audiometry were investigated in the present study.

1. The brainstem response threshold was compared with the pure tone audiogram in 40 patients with conductive hearing loss. The brainstem response threshold has a one to one relationship with the mean of the pure tone thresholds at 2 and 4 kHz. The correlation coefficient in this comparison is 0.84 and the standard error of the estimate is 8.3 dB. Taking into account corresponding results in cochlear hearing loss (chapter II) it is concluded that the brainstem response threshold provides a good estimate of the amount of peripheral hearing loss. independent of the type of hearing loss.

2. In chapter V it was shown that different types of peripheral hearing loss can be distinguished reliably with brainstem response audiometry. Parameters relevant for this distinction were the horizontal shift of the latency-Level curve (l(L)-curve) that of its derivative and the response threshold. In the clinical situation measurement of the response threshold is not always possible due to restlessness of the patient. To simulate this situation we randomly truncated the lower parts of the l(L)-curves of quiet patients. The test group consisted of 22 adult normally hearing subjects. 79 patients with cochlear hearing loss. 40 with conductive hearing loss and 22 with mixed hearing loss. Linear discriminant analysis was applied to the horizontal shift of the l(L) curve and of its derivative. The brainstem diagnosis "normal hearing" correctly excludes a conductive hearing loss in 98% of the cases and the brainstem diagnosis "cochlear hearing loss" does so in 79%. The brainstem diagnosis "conductive hearing loss" correctly predicts a conductive component of hearing loss in 94% of the cases and the brainstem diagnosis "mixed hearing loss" does so in 90%. The distinction between cochlear hearing loss and normal hearing is not reliable. neither is the distinction between conductive and mixed hearing loss.

3. The amount of the conductive component of hearing loss can be estimated by the horizontal shift of the l(L) curve. Statistical comparison with the mean of the air-bone gaps at 2 and 4 kHz gave a correlation coefficient of 0.77. a standard error of the estimate of 9.7 dB. and a slope of the regression line of 0.93. An overestimation of about 7 dB has to be taken into account in case of mixed hearing loss.

Résumé

Dans cette étude on a examiné trois aspects du potentiel evoqué du tronc cérébral.

1. Le seuil de ce potentiel a été comparé avec l'audiogramme chez 40 patients ayant une surdité de conduction. Le sueil de ce potentiel a une relation d'un sur un avec la moyenne des seuils d'audiogramme à 2 et à 4 kHz. Dans cette comparaison. le coefficient de corrélation est de 0.84. et la déviation standard de la détermination est de 8.3 dB. En tenant compte des résultats correspondants dans les surdites de perception (chapitre II) on peut conclure que le seuil du potentiel évoqué du tronc cérébral procure une bonne détermination de la mesure de surdite périphérique. quel que soit le type de surdité.

2. Auparavant (chapitre V) il a été démontré que dans les potentiels évoqués du tronc cérébral on peut distinguer avec fiabilite des types differents de surdité periphérique. Les paramètres pour cette distinction étaient le deplacement horizontal de la courbe de latence et d'intensité, celui de sa courbe dérivée et le seuil du potentiel. Dans la situation clinique, il n'est pas toujours possible de determiner le seuil du potentiel, a cause de l'agitation du patient. Pour simuler cette situation on a randomisé les parties inférieures des courbes de patients tranquilles. Le groupe avec de personnes examinées comprend 21 adultes avec perception normale, 79 patients souffrant d'une surdité de percetion, 40 patients avec une surdité de conduction et 22 patients ayant une surdité mixte. L'analyse discriminante linéaire a été appliquée au deplacement horizontal de la courbe de latence et d'intensité et a sa dérivée. Quand le diagnostic du potentiel évoqué est 'perception normale' c'est dans 98% de cas qu'il exclut correctement une surdité de conduction. Pour le diagnostic 'surdité de perception', ceci est valable dans 79% des cas. Quand le diagnostic du potentiel évoqué est 'surdité de conduction' c'est dans 94% des cas qu'il prévoit correctement un component de conduction. Pour le diagnostic 'surdité mixte' ceci est valable dans 90% des cas. Le distinction entre la surdité de perception et la perception normale est imprécise. Il in est de même pour la distinction entre la surdité de conduction et la surdité mixte.

3. On peut estimer la composante conductible de surdité par le déplacement horizontal de la courbe I(L). La comparaison statistique au moyen d'"air-bone gaps" a 2 et a 4 kHz a donné un coefficient de corrélation de 0.77 une déviation standard de la détermination de 9.7 dB et une inclinaison de la ligne de régression de 0.93. En cas de surdité mixte il faut tenir compte d'une surestimation d'environ 7 dB.

Introduction

Brainstem response audiometry has nowadays become part of clinical routine. However, it is not known exactly how reliable the method is. We have assessed some aspects of the reliability in previous studies. The present study deals with three more practical questions.

1. The brainstem response threshold in conductive hearing loss.

The auditory brainstem response threshold has been shown to be a useful instrument for estimating the amount of high frequency cochlear hearing loss (chapter II). The response threshold shows a good correspondence with the mean of the pure tone thresholds at 2 and 4 kHz.
The brainstem response threshold can also be used to distinguish between different types of hearing loss (cochlear, conductive or mixed hearing loss). For this it is necessary to determine the response threshold in combination with the horizontal shift of the peak V's latency-Level curve (l(L) curve) (also known in as latency-intensity curve) and the horizontal shift of its first derivative. A linear combination (derived by discriminant analysis) of these 3 parameters enables the classification of hearing losses in the 3 catagories mentioned above and also the calculation of the reliability of this classification: in an earlier study cochlear hearing loss and hearing loss with a conductive component were classified in this way and the results corresponded with the classification results based on the audiogram in 90% of the cases (chapters IV and V).

The reliability of the brainstem response threshold for estimating the amount of hearing loss has not yet been assessed for conductive hearing losses. It is one of the aims of this study to present such an assessment. If the amount of conductive hearing loss can be estimated as reliably as that of cochlear hearing loss for corresponding frequencies, the response threshold can be used to estimate the amount of a hearing loss independently of its etiology.

2. Determination of the type of hearing loss when the brainstem response threshold cannot be measured.

In clinical practice brainstem response audiometry is frequently used in patients in whom it is often the only method of determining hearing acuity. In such cases we also have to establish the type of hearing loss from the brainstem response data. It has already been shown that it is not possible to discriminate satisfactorily between the conductive and mixed types of loss (chapter V). The existence of a conductive component in a hearing loss, however, could be accurately predicted: the brainstem diagnosis "conductive hearing loss" correctly predicted a conductive component in 100% of the cases and the brainstem diagnosis "mixed hearing loss" was correct in 86% of the cases.
A complicating matter in this assessment is the impossibility of determining the brainstem response threshold in all cases, because of the restlessness of some patients. It is our experience that this happens in infants and children in about 15% of cases. Therefore it is of practical interest to know how reliable the brainstem response assessment of hearing loss is when we do not know the response threshold.
We can simulate this condition by randomly truncating the l(L) curves (as described in more detail in the section on data processing). Then the classification procedure, described in chapter V can again be applied. Thus a second aim of this study is to assess the reliability of classification of hearing losses by using linear discriminant analysis of brainstem response data when the response threshold is not known.

3. Determination of the size of the conductive component in hearing loss.

Even if the existence of a conductive component in a hearing loss can be confirmed reliably by a classification based on brainstem response data (with or without use of the response threshold), we still need to know the degree of reliability with which the size of this conductive component can be determined. In the literature (see next section), it is suggested that this can be measured by the horizontal shift of the l(L) curve. The third aim of the study focusses on the reliability of this procedure.

Yamada et al.(1975) studied the brainstem responses in 23 subjects with conductive hearing loss. Eleven of these conductive hearing losses were artificially induced by ear plugs. Yamada et al. plotted the l(L) curves for peak V of the subjects together with the reference curve. He calculated the amount of hearing loss in the ears tested by measuring the horizontal shift of the patient curve in relation to the reference curve at threshold level. Yamada et al. found that the thus determined loss correlated best with the pure tone threshold at 4 kHz. In 83% of the cases the difference between the two measurements was 15 dB or less. The proportion of patients with ear plugs in the given 83% was not mentioned. The air conduction thresholds in this comparison ranged from 15 to 50 dBHL.

Suzuki and Suzuki (1977) measured click stimulated auditory brainstem responses and pure tone audiograms in 20 children with otitis media with effusion and in 10 children with normal hearing. The averaged Fletcher index for the pure tone audiograms of the children with OME differed by 16 dB from that for the group with normal hearing. The amount of hearing loss in the test group with OME measured by brainstem response audiometry (similar to Yamada et al.(1975)) ranged from 15 to 20 dB. The range of the pure tone thresholds was not mentioned. neither was any further analysis reported in comparing the two measurements.

Fria and Sabo (1979) conducted a study similar to that of Yamada et al.(1975). They also found that the best correlation between the hearing losses as predicted by brainstem response audiometry and the pure tone threshold was at 4 kHz. The difference between the two measurements was less than 15 dB in 7 of the 10 subjects.

Borg et al.(1981) studied auditory brainstem responses in 10 subjects with conductive hearing loss. Their main objective was to find what correction was required when the existence of conductive hearing loss made it difficult to diagnose retrocochlear pathology using brainstem audiometry. They mentioned a correlation of 0.84 between the horizontal shift of the l(L) curve and the air-bone gap in the tone audiogram at 3 kHz. No information was given on the range of the conductive components.

McGee and Clemis (1982) used a slightly different method to calculate the horizontal shift of the patient l(L) curve. In a group of patients with conductive hearing losses they took the horizontal distances between all the data points of a patient's curve and the reference curve. The amount of hearing loss was estimated by averaging the distances. Tone pips of 1. 2 and 4 kHz were used as stimuli in brainstem response audiometry. In a scatterplot they showed the shift of the l(L) curve as a function of the air-bone gap in the tone audiogram in 5 ears with artificially-induced conductive hearing loss (ear plugs) and in 15 ears with middle

ear effusion. A line with a slope of 45° and a zero intercept was drawn through the data. All but 6 data points were within 10 dB of this line. In another scatter plot similar data were given for 7 ears with otosclerosis and 5 ears with ossicular chain discontinuity. The data showed somewhat more scatter and a line. fitted by eye (by the authors of the present study) suggests a slope that deviated considerably from 45°. In both figures one ear can be represented by between one and 3 data points (for the 3 frequencies). McGee and Clemis did not report to what extent deviating data points came from different patients.
Chisin et al.(1983) conducted a study in 32 subjects with conductive hearing loss. They plotted the latencies of peak I and peak V in click-stimulated brainstem response audiometry against various air conduction thresholds and air-bone gaps in the tone audiogram. In the total group the highest correlation was found between the latency of peak I and the air conduction threshold at 4 kHz ($r=0.62$). In this case the hearing loss ranged from 10 to 50 dB. The best relationship was found in a subset of the population: 10 patients with OME. For this group the correlation coefficient between the latency of peak I and the air conduction threshold at 0.5 kHz was 0.66. the standard error of the estimate was 6.1 dB. No information was given on the range of hearing losses in this subset of the population.

In summary. the literature indicates that in cases of conductive hearing loss the horizontal shift of the I(L) curve can be used to give an estimate of the amount of hearing loss. However. the number of ears tested are small in most studies. as are the ranges of hearing losses involved. Therefore the presented data do not often allow a clear interpretation or comparison with other studies.

Summarizing the preceding considerations we come to the following questions:

1. What is the relationship between the auditory brainstem response threshold and the pure tone threshold in conductive hearing loss?

2. How reliable is the classification of hearing losses based on linear discriminant analysis of brainstem response data. when the response threshold is not known?

3. How valuable is the horizontal shift of the I(L) curve for estimating the amount conductive hearing loss or the relative size of the conductive component in mixed hearing loss?

Procedures

Equipment and measurement methods

The equipment is described in detail in chapter II. (See table I of this chapter for summary).

Table I. Summary of data on measurement technique

Click polarity	alternating
Click duration	100 μs
Click repetition frequency	20 Hz
Headphone	TDH-39
Electrode impedances	< 2 kΩ
Filter bandwidth	10-4000 Hz
Filter slopes	24dB/oct.
Number of runs	2048
Artifact rejection levels	-12.5 to $+12.5$ μV
Time resolution	29.3 μs

The initial stimulation level was 100 dBnHL. Depending on the resulting response. the level was increased or decreased in steps of 10 dB until the threshold level was approached. The threshold level was defined as the lowest stimulation level with a reproducible peak V in the response. The threshold level was determined in steps of 5 dB. All responses were assessed by two experienced observers [M.B.. F.v.d.D] who had no knowledge of the pure tone audiogram.

Patient selection

The test population was described previously in the chapters IV and V. In table IIa the selection criteria are summarized for the "extrinsic" classification of the subjects using the tone audiogram to indicate whether they have normal hearing or conductive. cochlear. or mixed hearing loss. The number of male and female subjects in each group and also the ranges and the means of their ages are given in table IIb.

Data processing

To compute the horizontal shift of the l(L)-curve in each case. the level differences between the individual and the reference curve were measured and averaged in the way described by McGee and Clemis (1982). Peak V latencies below 5.9 ms were not included in the calculations. (Chapter III).

Table IIa. Selection criteria for the 'extrinsic' classification of normal hearing and cochlear, conductive or mixed hearing loss using the tone audiogram.

normal hearing	mean air conduction threshold	$\leqslant 7.5$ dBHL
	no air conduction threshold	> 15 dBHL
cochlear	mean air bone gap	< 7.5 dB
	no air bone gap	> 10 dB
conductive	mean bone conduction threshold	< 15 dBHL
	no bone conduction threshold	> 20 dBHL
mixed	mean air-bone gap	$\geqslant 7.5$ dB
	air conduction threshold	> 15 dBHL

Table IIb. Ages and numbers of subjects in the four subgroups of the test population, after truncation of l(L) curves (see Data processing). In all cases one ear per subject was included.

	age in years		**number**	
	mean	**range**	**male**	**female**
normal hearing	27	20-40	12	10
cochlear hearing loss	45	10-85	30	37
conductive hearing	24	10-45	23	17
mixed hearing loss	34	10-85	12	5

Derived l(L)-curves were obtained by piecewise linear approximation by taking the differences between the latencies of peak V per 10 dB difference in stimulation level. The horizontal shifts of the thus formed derivatives of the l(L) curves relative to the derivative of the reference curve were calculated in a similar way to the horizontal shifts of the l(L)-curves themselves. (Chapters IV and V).

To investigate the value of brainstem response audiometry for identifying and measuring conductive hearing loss without the use of the response threshold the following model was chosen: the lower-level parts of all l(L) curves in the entire test population were truncated randomly; the numbers of data points removed from each patient's l(L) curve were randomly drawn from a uniform distribution between 2 and (n-2), where n is the total number of data points per l(L) curve. Classification of the hearing losses was done by linear discriminant analysis using the horizontal shifts of the truncated l(L) curve and its derivative in a similar way to that described in chapter V.

Results

1. The relationship between the brainstem response threshold and the pure tone audiogram in conductive hearing loss

Table III. Statistical analysis of the difference between the auditory brainstem response threshold and the air conduction threshold for the octave frequencies between 0.25 and 8 kHz and for the means of 2 and 4 kHz.

Relations PTA-ABRT	**Pure-tone frequency (kHz)**						
	0.25	**0.50**	**1.0**	**2.0**	**4.0**	**8.0**	**2-4**
Mean difference, dB	−4.0	−10.0	−14.0	−13.4	−1.3	−0.7	−6.0
Standard deviation of difference, dB	15.9	15.5	14.0	9.8	11.6	13.3	8.7
Correlation coefficient	0.56	0.57	0.63	0.80	0.72	0.58	0.84
Slope of the regression line	1.31	1.32	1.16	0.96	0.98	0.88	0.96
Standard error of the estimate	14.2	13.8	12.8	9.4	10.8	11.7	8.3

Table III shows the results of the statistical comparison of the brainstem response threshold with the air-conduction threshold for the group of patients with a pure tone audiogram of the conductive type (n=40). Plots of the correlation coefficients and the standard errors of the estimate as a function of the tone frequencies are given in fig.1 (The dotted vertical line represents the mean of 2 and 4 kHz). The best correspondence between the response threshold and the tone threshold is found for the mean of the pure tone thresholds at 2 and 4 kHz, giving a correlation coefficient of 0.84, a standard error of the estimate of 8.3 dB and a regression line given by the function Y=0.96X-5 dB.[1]
The data from which this best correspondence is derived are shown in fig.2, a scatter plot with the mean of the air conduction tone thresholds at 2 and 4 kHz against the response threshold.

2. Distinguishing between different types of hearing loss without knowledge of the response threshold.

All ears in the entire test group (n=146) were classified by linear discriminant analysis into the 4 categories normal hearing, cochlear, conductive or mixed hearing loss. The same procedure was followed as described in chapter V, but now

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[1] The regression analysis was done in both directions, yielding 2 slope coefficients. Because both thresholds are measurements with about equal inaccuracy, the slope coefficient given is the mean of the 2 slope coefficients.

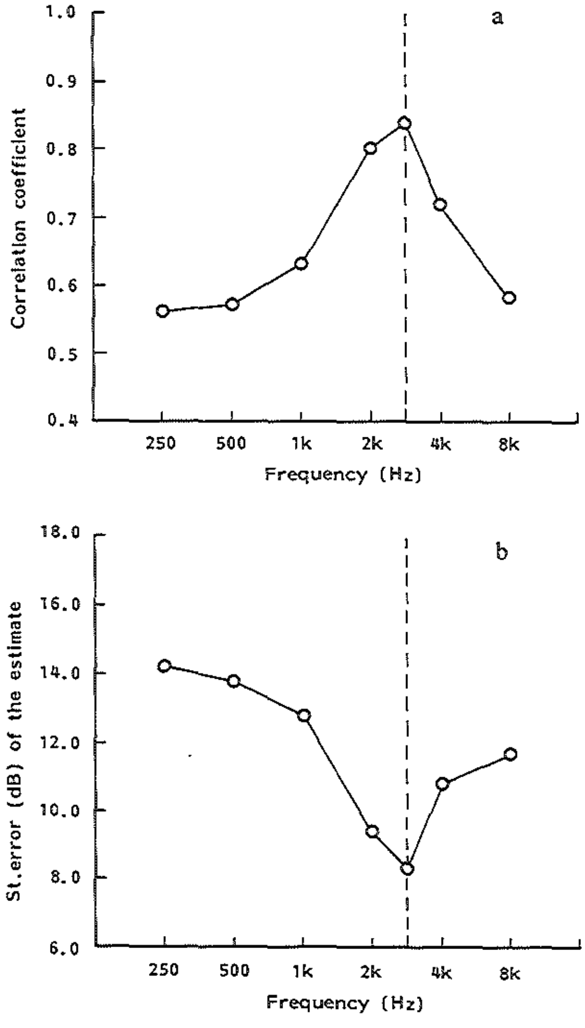

Fig. 1

Results of the regression analysis between the auditory brainstem response threshold and the pure tone audiogram as a function of the frequencies of the audiogram.

1a : correlation coefficient

1b : standard error of the estimate

The dotted vertical line represents the mean of 2 and 4 kHz.

analysis and classification were done on truncated l(L) curves and their derivatives and no response thresholds were included. The parameters and Fisher-functions for the classification are given in Appendix A.

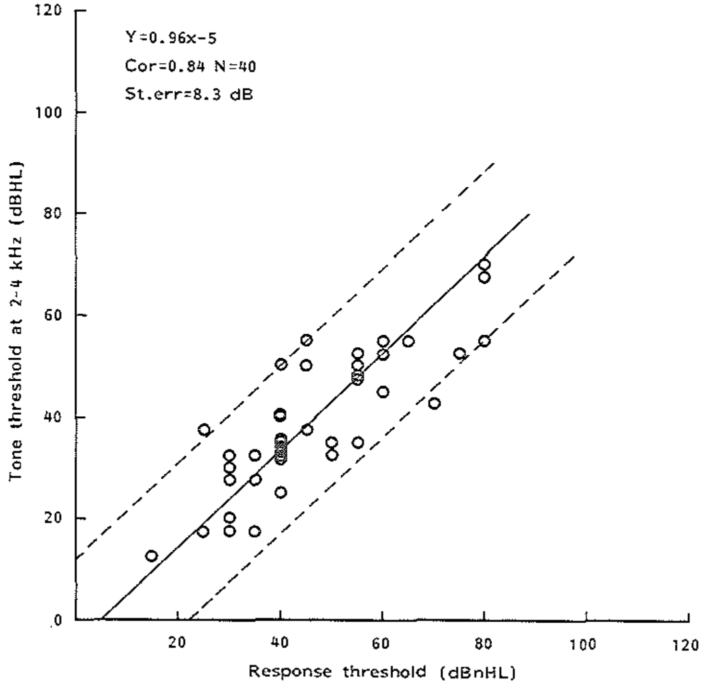

Fig. 2
Scatter diagram of the average of the pure tone air-conduction thresholds at 2 and 4 kHz versus the auditory brainstem response threshold in conductive hearing loss.

The results of this procedure are presented in table IV. It shows in parentheses the number of ears that are classified by brainstem response data as normal or suffering from cochlear, conductive or mixed hearing loss; the data are also subdivided by the classification based on the pure tone audiogram. The percentages shown are indirectly related to the actual number of ears; the percentages show the results that are found if the numbers of ears in the 4 audiogram categories are assumed to be equal.

Thus, for instance, if an ear suffers from conductive hearing loss according to brainstem response data (third line), in 55% of cases this is in agreement with the classification according to the tone audiogram, 39% of these ears were classified by the tone audiogram as having mixed hearing loss and 6% as having cochlear hearing loss.

Table IV. Cross-classification table, giving normal hearing, cochlear, conductive, and mixed hearing loss obtained from brainstem response data without response threshold and discriminant analysis against the 'extrinsic' classification using the tone audiogram. The figures have been corrected to give equal numbers in each of the four subsets of the population. The actual number of ears are given within parentheses.

ABR without resp. thresh.+disc. anal.	**tone audiogram**				
	normal	**cochlear**	**conductive**	**mixed**	**total**
normal	66 % (19)	32 % (28)	2 % (1)	0 % (0)	100 %
cochlear	19 % (3)	60 % (28)	21 % (6)	0 % (0)	100 %
conductive	0 % (0)	6 % (4)	55 % (20)	39 % (6)	100 %
mixed	0 % (0)	10 % (7)	30 % (13)	60 % (11)	100 %

3. The horizontal shift as an estimate of the conductive component in hearing loss.

A statistical comparison between the horizontal shift of the I(L) curve and the mean of the pure tone air conduction thresholds at 2 and 4 kHz gave a correlation coefficient of 0.82, a standard error of the estimate of 9.1 dB and a slope coefficient of the regression line of 0.88. Fig.3 shows the corresponding scatter plot.

Discussion

1. The relationship between the brainstem response threshold and the tone audiogram in conductive hearing loss.

Comparing the results of the present study with those of chapter II, the smallest standard error of the estimate in conductive hearing loss (8.3 dB) appears to be significantly smaller than that in cochlear hearing loss (11.1 dB) (F-test: $p<0.01$). In the population with normal hearing the standard error of the estimate in a similar regression analysis is 5.0 dB. This is significantly smaller than in either conductive or cochlear hearing loss (F-test: $p<0.01$). Apparently both middle and inner ear pathology introduce factors which cannot be accounted for in the relationship between the brainstem response threshold and the pure tone threshold.

The significant difference between the standard errors of the estimate in cochlear and conductive hearing loss indicates that the effect of pathology on the relationship between the two measurements is larger in cochlear than in middle ear pathology.

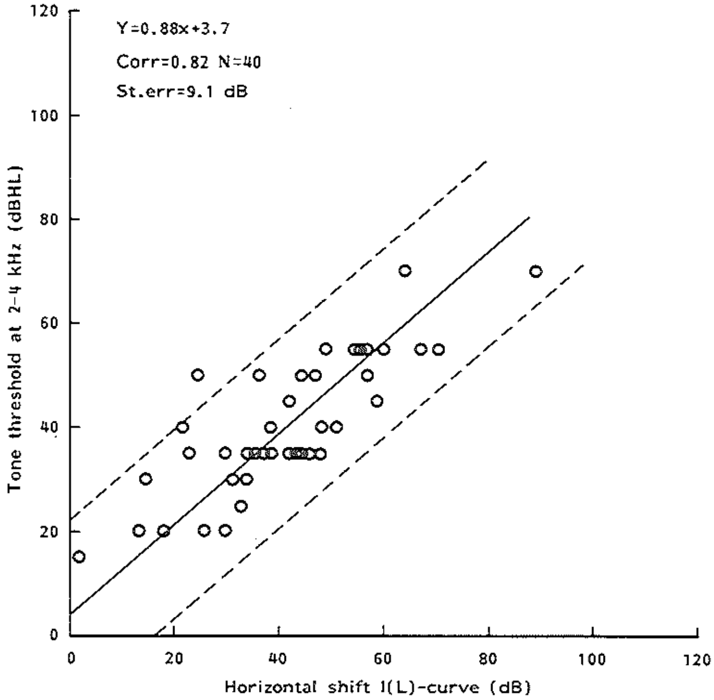

Fig. 3
Scatter diagram of the average of pure tone thresholds at 2 and 4 kHz versus the horizontal shift of the I(L) curve in conductive hearing loss.

Regression analysis is the suitable instrument for estimating how closely the two measurements are related. However, one must be aware of the limited value of regression parameters such as the correlation coefficient. For instance, in the present study the correlation coefficient between the brainstem response threshold and the average of the pure tone thresholds at 2 and 4 kHz (0.84), is smaller than the corresponding figure for cochlear hearing loss (0.93) (chapter II). At first sight this suggests a better relationship between the two measurements in cochlear hearing loss than in conductive hearing loss. However, the situation is the reverse for the standard error of the estimate (11.1 dB for cochlear hearing loss and 8.7 dB for conductive hearing loss) which suggests a better relationship between the two measurements in conductive hearing loss. This difference is caused by the wider dynamic range in cochlear hearing loss.

From the comparison of the relationships between the brainstem response threshold and the tone audiogram in cochlear and conductive hearing loss we conclude that the former provides a good estimate of the total amount of peripheral hearing loss. independent of the etiology of the hearing loss.

2. Distinguishing between different types of hearing loss without knowledge of the response threshold.

As was mentioned in the introduction. in the practical situation brainstem response data are frequently the only data available for classifying hearing loss while the response threshold is not always known either. because of the restlessness of the patient. In the present chapter we have also paid attention to the value of brainstem response data in this situation. This was done by simulating the restlessness condition by randomly truncating the I(L) curves of adult patients (see section on Data processing).
Of course every simulation has its drawbacks. In this case one has to trust that the resulting distribution of the differences between the lowest stimulation level used and the response threshold level is representative for that in the target group. The only way to determine the real shape of this distribution would be to measure a consecutive group of children and infants both with and without sedation/narcosis on the same day. This procedure is not feasible in a clinical situation because of practical and ethical difficulties.
To distinguish between cochlear hearing loss and normal hearing one depends on the very lower part of the curve which is actually missing in restless patients. So. if the response threshold is missing. the distinction between normal hearing and cochlear hearing loss is not reliable. This is confirmed by the data in table IV. which show the results of classification based on brainstem response data without the response threshold. The brainstem diagnosis "normal hearing" is in agreement with the tone audiogram in only 66% of the cases. In 32% of cases a cochlear hearing loss is missed. The brainstem diagnosis "cochlear hearing loss" is in 60% of cases in agreement with the tone audiogram. However. the brainstem diagnosis "normal hearing" correctly excludes a conductive component of hearing loss in 98% of the cases and the brainstem diagnosis "cochlear hearing loss" does so in 79%.
In cases with the brainstem diagnosis "conductive" or "mixed hearing loss" a considerable percentage of the ears has an audiogram indicating the "mixed" or "conductive" type. respectively. The only question therefore that can be answered reliably about the hearing loss involved is whether there is a conductive compo-

nent or not. As to the prediction of a conductive component in hearing loss. the brainstem diagnosis "conductive hearing loss" correctly predicts a conductive component in 94% of cases. and the brainstem diagnosis "mixed hearing loss" does so in 90% of the cases. Ears with normal hearing were never diagnosed as having a conductive component. Apparently it is possible to make a reliable distinction between normal hearing and conductive hearing loss without use of the response threshold.

To compare the classifications with and without using the response threshold. a similar classification is given in table V for the same subjects as in table IV. now using the complete I(L) curves. including threshold data. The brainstem diagnoses "normal hearing" and "cochlear hearing loss" are. as was to be expected. considerably more reliable when the response threshold is also used. correctly predicting 79% and 87% respectively. The identification of a conductive component in hearing loss does not become more reliable with use of the response threshold: the brainstem diagnoses "conductive" and "mixed hearing loss" correctly predict a conductive component in hearing loss in 97% and 87% of cases respectively. Also the reliability of the distinction between conductive and mixed hearing loss is similar with and without use of the response threshold.

Table V. Cross-classification table, giving normal hearing, cochlear, conductive and mixed hearing loss obtained from brainstem response data including the response threshold and discriminant analysis against the 'extrinsic' classification using the tone audiogram. The classification has been done for the same test group as that in table IV. The figures have been corrected to give equal numbers in each of the four categories of hearing loss. The actual number of ears are given within parentheses.

ABR with resp.	**tone audiogram**				
thresh.+disc. anal.	**normal**	**cochlear**	**conductive**	**mixed**	**total**
normal hearing	79 % (22)	15 % (13)	6 % (3)	0 (0)	100 %
cochlear	0 % (0)	87 % (45)	13 % (4)	0 % (0)	100 %
conductive	0 % (0)	3 % (2)	61 % (28)	36 % (7)	100 %
mixed	0 % (0)	13 % (7)	15 % (5)	72 % (10)	100 %

Although we have to keep in mind that the restless condition of patients was merely approximated by a simulation model. we can conclude that identification of a conductive component in hearing loss can be done reliably. even if the brainstem response threshold is unknown.

3. Determination of the size of the conductive component in hearing loss.

In cases where the type of hearing loss is known to be conductive (for instance. when cochlear hearing loss has been excluded in a previous examination). the standard error in estimating the air-conduction tone threshold from the response threshold is 8.3 dB and 9.1 dB from the horizontal shift of the l(L) curve. The difference between both standard errors of the estimate was not significant (F-test).

It is clear from the results that in these cases the response threshold is the best measurement of the amount of loss and that the horizontal shift is an almost equally reliable alternative.

Comparison of the results of the present study with the data in the literature is possible only to a limited extent. Yamada et al.(1975) reported that 80% of the predictions for the means of the pure tone thresholds at 0.5. 1 and 2 kHz were correct within 15 dB. In the present study 95% of the means of the pure tone thresholds at 2 and 4 kHz were predicted correctly within 16 dB. a result somewhat better than but not dissimilar from that obtained by Yamada et al.

The range of the hearing losses in the studies by Suzuki and Suzuki (1977). Fria and Sabo (1979) and Borg at al.(1981) are rather small. Therefore their correlation coefficients can not be compared directly with ours. McGee and Clemis (1982) show a dynamic range of hearing losses that is comparable to that in the present study. They do not present statistics as we do. but a comparison of their scatter diagram No.1 with fig.3 in the present study gives a close similarity.

In summary. in cases where the hearing loss is known to be conductive. we find that the horizontal shift of the l(L) curve yields at least as good an estimate of the amount of hearing loss as suggested by the literature.

As was shown above. it is not possible to distinguish satisfactorily between conductive and mixed hearing loss using brainstem response data. Part of the overlap between the hearing losses with a conductive and a mixed type audiogram is caused by the troublesome composition of the group with mixed hearing loss: in spite of the criteria chosen for classification of the hearing losses based on the audiogram (see table II). it is probable that a number of purely conductive losses were incorrectly put into the mixed group. due to the Carhart notch phenomenon.

In the clinical situation the effect of the overlap between ears with conductive and those with mixed hearing loss is smaller than it seems, because in the target group of patients the prevalence of the mixed hearing losses is much smaller than that of conductive hearing loss.

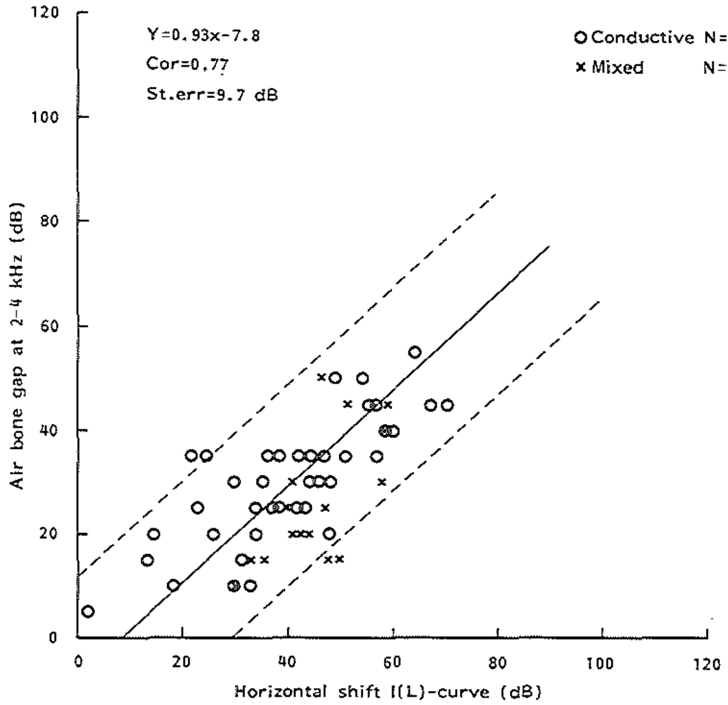

Fig. 4

Scatter diagram of the average of the air-bone gaps at 2 and 4 kHz versus the horizontal shift of the I(L) curve in conductive hearing loss (circles: n=40) and in mixed hearing loss (crosses: n=17). The given results of regression analysis and the drawn regression line are based on the conductive hearing losses.

Therefore we suggest using the horizontal shift of the I(L) curve for estimating the air-bone gap of ears that are classified as having conductive or mixed hearing loss according to brainstem response data. An indication of the reliability of the method is shown in fig.4. In this scatter plot the mean of the air-bone gaps at 2 and 4 kHz is given as a function of the horizontal shift of the I(L) curve in the ears with an audiogram of the conductive type (circles: n=40). The corresponding data for ears with audiograms of the mixed type are added as crosses (n=17). The given results of regression analysis are based on the data in the group with conductive type audiograms: the correlation coefficient is 0.77, the standard error of the estimate is 9.7 dB and the regression line follows the formula Y=0.93X-7.8 dB.

Taking this regression equation for the two groups we compared the mean and the variance of the distributions of the residuals for the conductive and the mixed group, in order to evaluate the error in cases of mixed hearing loss. No significant difference was found between the variances in the two groups (F-test). Naturally the mean in the conductive group is 0 dB. That for the mixed group was -6.8 dB and differed significantly from zero (T-test; $p<0.05$).
We conclude that when a hearing loss is classified as conductive or mixed, the best we can do is to estimate the air-bone gap from the horizontal shift of the I(L) curve, taking into account an over-estimation of 7 dB in cases of mixed hearing loss.

Clinical impact

The consequence for the clinical practice is that when the brainstem diagnosis without response threshold is "conductive" or "mixed hearing loss", ENT treatment for a probable conductive component of hearing loss is indicated. The size of the conductive component can be estimated to a certain extent. The next step will be repeated measurement under sedation or general anaesthesia. Without data on the response threshold the reliability of the brainstem diagnoses "cochlear hearing loss" and "normal hearing", is low. In these cases repeated measurement under sedation or general anaesthesia is needed in any case.

Summarizing the data and their interpretation as given above, we come to the following conclusions:

Conclusions:

1. The brainstem response threshold provides a good estimate of the amount of hearing loss at 2 and 4 kHz. This is true for conductive hearing loss as well as for cochlear hearing loss.

2. Brainstem response audiometry is a useful instrument for identifying the conductive component in hearing loss. This determination can be carried out even when the brainstem response threshold is not available.

3. If a conductive component is identified, its amount can be estimated by studying the horizontal shift of the I(L) curve, taking into account an overestimation of 7 dB in cases of mixed hearing loss.

Appendix A

The linear classification function that is used is represented by the formula:

$$Y_{lin} = b_0 + b_1X_1 + b_2X_2 + \dots + b_nX_n$$

Y_{lin} is the classification score: b_0 is a constant provided by the analysis: b_1. b_2 etc. are the classification coefficients provided by the analysis and by weighing the predictor variables X_1. X_2 etc.. In this study X_1 etc. represent the brainstem data from which the classification has to be made: the horizontal shift of the l(L) curve and the shift of the derivative of this curve.

The type of hearing loss with the highest classification score should be chosen. For our material the classification functions are:

Cs(normal) = -0.015(l(L)-shift) + 0.042(l'(L)-shift) - 1.485

Cs(cochlear) = 0.040(l(L)-shift) + 0.063(l'(L)-shift) - 2.169

Cs(conductive) = 0.110(l(L)-shift) + 0.160(l'(L)-shift) - 6.680

Cs(mixed)= 0.168(l(L)-shift) + 0.111(l'(L)-shift) - 7.360

References

Borg E., Lofqvist L., Rosen S.
Brainstem responses in conductive hearing loss
Scand. Audiol. 1981. suppl. 13: 395-400

Chisin M., Gafni M., Sohmer H.
Patterns of auditory nerve and brainstem evoked responses in different types of hearing loss
Arch. Otorhinolar. 1983. 237: 165-173

Fria T.J., Sabo D.L.
Auditory brainstem responses in children with otitis media with effusion
Ann. Otol. Rhinol. Laryngol. 1979. 89/3 II suppl. 68: 200-206

McGee T.J., Clemis J.D.
Effects of conductive hearing loss on the auditory brainstem response
Ann. Otol. Rhinol. Lar. 1982. : 304-309

Suzuki M., Suzuki J.I.
Clinical application of the auditory evoked brainstem response in children
ANL 1977. 4: 19-26

Yamada O., Kodera K., Yamane H., Suzuki J.I.
Clinical evaluation of the auditory evoked brainstem response
ANL 1975. 2: 97-105

Chapter VII

Summary and concluding remarks

The results of click-stimulated brainstem response audiometry were compared with the results of pure tone audiometry in adult patients. The comparison focussed on two aspects: the measurement of the amount of hearing loss and the distinction between different types of hearing loss. In addition to what has been reported in chapters II-IV both aspects will be discussed briefly in the following two sections. surveying the results of the present study and dealing with the consequences for the clinical practice and suggestions for further research.

1. The auditory brainstem response threshold as an estimate of the amount of hearing loss

In chapter II and chapter VI the relationship between the auditory brainstem response threshold and the pure tone threshold is investigated. Both in cochlear and in conductive hearing loss a one-to-one relationship has been demonstrated between the response threshold and the mean of the air-conduction tone thresholds at 2 and 4 kHz. The correlation coefficients between the objective (brainstem response threshold) and the subjective (pure tone threshold) measurements were 0.93 and 0.84 for cochlear and conductive hearing loss: The standard errors of the estimate were 11.1 dB and 8.3 dB.
It was shown in a test-retest experiment. described in chapters II and III. that in adult patients the brainstem response threshold can be measured just as accurately as the pure tone threshold. The inaccuracy of the brainstem response threshold in normal hearing and in cochlear hearing loss was less than 4 dB. This is in the same range as the inaccuracy in the pure tone thresholds at 2 and 4 kHz according to the ISO standard (1983): 2.8 and 3.7 dB.
Contrary to previous reports (Coats and Martin (1977). Jerger and Mauldin (1978). Kavanagh and Beardsley (1979). Bellman et al.(1984)) we conclude from the above figures that the brainstem response threshold provides as good an estimate for the amount of hearing loss at 2 and 4 kHz as the pure tone audiogram. irrespective of the type of hearing loss.

In chapter II the limitations of using the brainstem response threshold were demonstrated. The strong relationship between the response threshold and the tone audiogram is only valid in the 2 and 4 kHz region. An instructive illustration was given in fig.3 of chapter II. showing that the brainstem response threshold can be normal in the presence of a considerable hearing loss at the low frequencies. Other methods must be developed for cases in which information on the low frequency is essential. Brainstem response audiometry using tone pips (H.Davis et al.(1984,1985)) and masking technics (Eggermont and Don (1980), Van Zanten and Brocaar (1984)) have been reported to enable a good estimation of the hearing threshold al low frequencies in normal hearing individuals. However, the feasibility of these methods in examining patients with hearing disorders remains to be studied. Also the use of the middle latency response and especially the 40 Hz Event-Related Potential (Galambos et al.(1981)) could be considered a promising method for determining a frequency-specific threshold, if ways can be found to stabilize the cortex in the required stage of wakefulness.

2. Distinction between different types of hearing loss using brainstem response data

The second aim of the present study was to investigate the reliability of brainstem response audiometry with air conducted click stimulation for distinguishing between different types of peripheral (i.e. cochlear, conductive, mixed) hearing loss. The position of the l(L) curve of peak V (including the threshold point) relative to the reference curve was considered the main piece of evidence in making this distinction. Therefore the inaccuracy of this curve was studied.

It was shown in a test-retest experiment (chapter III) that the inaccuracy of the latency of peak V is about 0.1 ms at high stimulation levels and increases to about 0.2 ms near the threshold level. Because the horizontal shift of the l(L) curve (in dB) is an important factor in monitoring conductive hearing loss, the inaccuracy in latency (in ms) was converted into an inaccuracy in level (in dB). For the longer latencies the inaccuracies in level appeared to be smallest: <4 dB. For latencies shorter than 6 ms there is a sharp increase in the inaccuracy in level, to more than 13 dB (chapter III, fig.1). Therefore we excluded the part of the curve with latencies below 6 ms in further calculations of the horizontal shift of the l(L) curve in chapters IV to VI.

To distinguish between different types of peripheral hearing loss the position of the l(L) curve was analyzed by studying the following three aspects: the response threshold and the horizontal and vertical shift of the l(L) curve relative to the reference curve. An extra parameter was introduced to make a distinction between horizontal shift (typical for conductive hearing loss) and vertical shift (occasionally present in cochlear hearing loss): this parameter was the horizontal shift of the derivative of the l(L) curve (chapter IV).
Thus, we disregarded the possible change of shape of the l(L) curve. Changes of shape do occur however, especially in cochlear hearing loss. In an early stage of the investigation curve-fitting procedures were applied to all l(L) curves in order

to find whether there was any relationship between changes in the shape of the l(L) curve and the tone audiogram. The curve-fitting procedure was quite successful: a negative exponential function could be fitted through the l(L) curves with a mean error of 0.2 ms. However, no sensible relationship could be established between any shape parameter and the pathology or any other properties of the tone audiogram. Therefore it was considered not feasible to make a correction for changes in shape. We had to accept the extra variance in vertical and horizontal shift that are caused by changes in shape.

The three aspects mentioned - the response threshold and the horizontal shift of the l(L) curve and of its derivative - were combined into linear "classification" equations using discriminant analysis.
This procedure was demonstrated to provide a useful method for distinguishing between cochlear hearing loss and hearing losses with a conductive component as illustrated by the following figures. The brainstem-classification "cochlear hearing loss" agreed with the audiogram type in 86% of cases (mixed:11%; conductive:3%); the brainstem classification "conductive hearing loss" indicated a conductive component in 100% of cases and the brainstem classification "mixed hearing loss" did so in 86% of cases (chapter V, table III). The method was unsatisfactory for distinguishing between purely conductive and mixed hearing loss.

The use of brainstem response audiometry in children without narcosis or sedation is complicated by the impossibility of measuring the response threshold in 15% of cases because of the restlessness of the patient. In order to ascertain whether the method is nevertheless applicable for such patients this situation was simulated in our data on adults by randomly truncating the lower level parts of the l(L) curves (chapter VI). Analyzing the position of these truncated l(L) curves (i.e. without the response threshold) we obtained results similar to those just described (chapter VI, table IV): the brainstem diagnosis "normal hearing" excluded a conductive component in 98% of the cases and the brainstem diagnosis "cochlear hearing loss" did so in 79%: the brainstem diagnosis "conductive hearing loss" correctly predicted a conductive component in 94% of the cases and the brainstem diagnosis "mixed hearing loss" did so in 90%. The distinction between normal hearing and cochlear hearing loss could not be established without the response threshold.

The reliability of a method is often expressed in terms of sensitivity and specificity. If one wants to apply this approach to the results of the present study, this could be done by considering each brainstem diagnosis (including "normal hearing") against the total group of subjects. From table V in chapter VI it can be calculated that the brainstem diagnosis "normal hearing" has a sensitivity of 100% and a specificity of 91%. The sensitivity and the specificity of "cochlear hearing loss" are 67% and 97% respectively. Prediction of a conductive component was done with a sensitivity of 88% and a specificity of 93%.

It can be concluded that brainstem response audiometry. with or without the use of the response threshold. is especially a useful instrument for the identification of the conductive component in a hearing loss. For clinical practice. this means that the brainstem diagnosis "conductive" or "mixed hearing loss" is an indication for ENT evaluation and treatment. Because of the poor distinction between purely conductive and mixed hearing loss we have to be alert to some cochlear hearing loss remaining after treatment of the conductive hearing loss. Audiometry must be repeated in cases where there is any doubt. It can further be concluded that the brainstem diagnosis "cochlear hearing loss" is highly reliable provided that the response threshold can be measured. In that case the usual further treatment and instruction that goes with the diagnosis should take place without delay. When no response threshold is available it is only possible to exclude a conductive component. If this has been done. reexamination under sedation or anaesthesia is the logical next step to exclude cochlear hearing loss.

The clinician's diagnosis. of course. is based on more information than brainstem response audiometry alone. A combination of brainstem response audiometry and a good patient history. ENT-examination and tympanometry are essential if one is to come to an optimum judgement and clinical decision. The evaluation of the reliability of the combined clinical data is beyond the scope of the present thesis.

An alternative method for acquiring response data?

It would be a very welcome improvement if brainstem response audiometry could be made less time-consuming. One promising development in this respect is the idea of Thornton. of Harvard University (Thornton et al.(1985). Kileny (1987)). who proposes to replace the assessment of the mean amplitude of a response peak by comparing the distribution of the response amplitude with stimulation with that of the background noise. i.e. the "response" without stimulation. The method provides a real statistical test of the signal-to-noise ratio. in which both the mean and the standard deviation of the amplitude distributions are used to detect a response peak. This method probably requires fewer runs per stimulation level for the recognition of a response peak. If that is the case. the determination of the response threshold will take less time. A second advantage is that the subjective judgement of the observer as to whether a response contains a peak or not. will be replaced by an objective statistical criterion.
At this moment the general principle described above is used in a patented hearing screening device. Unfortunately the specifications of the method have not

been published. Therefore the basic research for that method must be repeated if we want to implement it for more elaborate investigation of hearing disorders.

Effects of the specifications of the technical equipment on the I(L)curve.

The quantitative rules for classification as demonstrated in the present study depend on the shape and position of the I(L) curve in normal hearing and changes in the curve due to ear pathology. The shape of the I(L) curve, however, can be influenced by the measurement conditions. Theoretically the filter settings of the equipment used in data acquisition and the stimulus wave form can be expected to influence the shape of the I(L) curve. In a pilot study we compared the shape of the I(L) curves measured with different types of headphones: a TDH 39 and an MSH 49. The I(L) curves measured using the MSH 49 headphone seemed to be slightly steeper and less curved than those measured using the TDH 39 headphone. Therefore the linear classification functions used in the present study are not necessarily applicable without modification in other clinics. Further research is has to reveal to what extent the shape of the I(L) curves and the resulting classification functions are effected by the measurement conditions. We are convinced however, that the principle of the method is generally applicable. Since the I(L) curves in a large number of settings have been demonstrated to show only slight differences in shape (Lazor and Melnick (1984)) probably only small deviations from our results will result, even when the classification rules are applied without further correction.

References

Bellman S.. Barnard S.. Beagley H.A.
A nine years review of 841 children tested by transtympanic electrocochleography
J. of Laryngol.and Otol. 1984. 98: 1-9

Coats A.C.. Martin J.L.
Human auditory nerve action potentials and brainstem evoked responses: effect of audiogram shape and lesion location
Arch. Otolaryngol. 1978. 103: 605-622

Davis A.E.. Barnard S.. Beagley H.A.
Acoustic brainstem responses for clinical use: a comparison of pure tone stimuli with wide band clicks
Clin. Otolaryngol. 1985. 10: 243-247

Davis H.. Hirsh S.K.. Popelka G.R.. Formby C.
Frequency selectivity and thresholds of brief stimulation. suitable for electric response audiometry
Audiology 1984. 23 (1): 59-74

Davis H.. Hirsh S.K.. Turpin L.L.. Peacock M.E.
Threshold sensitivity and frequency specificity in auditory brainstem response audiometry
Audiology 1985. 24 (1): 54-70

Eggermont J.J.. Don M.
Analysis of click-evoked brainstem potentials in man using high- pass noise masking. II. Effect of click intensity
J. acoust. Soc. Am. 1980. 68: 1671-1675

Galambos R.. Makeig S.. Talmachoff T.J.
A 40 Hz auditory potential recorded from the scalp
Proc. Natl. Acad. Sci. U.S.A. 1981. 78: 2643-2647

International Standard ISO 6189. First Edition 1983 -12-01

Jerger J.. Mauldin L.
Prediction of sensorineural hearing loss from the brainstem evoked response
Arch. Otolaryngol. 1978. 104: 456-461

Kavanagh K.T., Beardsley J.V.
Brainstem auditory evoked responses II: clinical application in the assessment patients with organic hearing loss
Ann. Otol. Rhinol. Laryngol. 1979. 88. suppl. 58: 11-21

Kileny P.R.
New insight on infant ABR hearing screening
Abstract. IVth Int. Symp. on Aud. Med. Tenerife. November 8-13. 1987

Lazor J.L., Melnick W.
A survey of current clinical procedures in use by audiologists to measure auditory brainstem responses
Sensory evoked potentials I. An international conference on standards for auditory brainstem response (ABR) testing
Edizioni tecniche. Milan 1984. 185-207

Thornton A.R., Sprague Herrmann D., Berrick J.M.
Automated neonatal hearing screening using the auditory brainstem response
Abstract D1. 9th international symposium E.R.A. study group
Erlangen sept. 2-5 1985

Zanten van G.A., Brocaar M.P.
Frequency-specific auditory brainstem responses to clicks masked by notched noise
Audiology 1984. 23: 253-264

Chapter VIII

Samenvatting

Voor een goede behandeling en begeleiding van slechthorende kinderen is het van groot belang, dat de diagnose slechthorendheid zo vroeg mogelijk wordt gesteld. Voor de vroegdiagnostiek van slechthorendheid is hersenstamaudiometrie bij uitstek geschikt, omdat bij deze meetmethode medewerking van de patiënt niet vereist is.

Doel van dit proefschrift is de validiteit van hersenstamaudiometrie te testen, door de resultaten te vergelijken met die van toonaudiometrie.

Aangezien voor toonaudiometrie medewerking van de patiënt wel vereist is, moest voor deze vergelijking gebruik gemaakt worden van gegevens van volwassen patiënten.

De vergelijking betreft twee aspekten van audiometrie, te weten de bepaling van de omvang van het gehoorverlies en het onderscheid tussen verschillende soorten gehoorverlies.

In dit proefschrift wordt het reeds uitgebreid bestudeerde onderscheid tussen cochleair en retrocochleair gehoorverlies buiten beschouwing gelaten.

1. De hersenstam responsdrempel als maat voor de omvang van het gehoorverlies

In hoofdstuk II en VI wordt de relatie tussen de hersenstam responsdrempel en de toondrempel onderzocht. De beste correlatie tussen beide testen wordt zowel bij cochleair als bij geleidingsverlies gevonden bij het gemiddelde van 2 en 4 kHz. De correlatiecoëfficiënt tussen de objectieve (hersenstam respons-) drempel en de subjectieve (toon-) drempel is 0.93 bij cochleair- en 0.84 bij geleidingsverlies. Zowel bij cochleair verlies als bij geleidingsverlies is de relatie tussen de hersenstam responsdrempel en het gemiddelde van de toondrempels bij 2 en 4 kHz één op één. De standard-errors of the estimate zijn respektievelijk 11.1 en 8.4 dB.

Met behulp van een test-retest experiment, beschreven in hoofdstuk II en III, werd aangetoond dat de hersenstam responsdrempel even nauwkeurig gemeten kan worden als de toondrempel. De onnauwkeurigheid van de hersenstam responsdrempel is minder dan 4 dB. Dit is in dezelfde orde als de toondrempel bij 2 en bij 4 kHz.

In tegenstelling tot eerdere berichten in de literatuur (zie hoofdstuk II), kan geconcludeerd worden, dat de hersenstam responsdrempel een even goede maat is voor de omvang van gehoorverlies bij 2 en 4 kHz is als het toonaudiogram, onafhankelijk van het soort gehoorverlies.

2. Onderscheid tussen verschillende soorten gehoorverlies

In verband met de zeer verschillende behandelingswijzen van cochleair en conductief gehoorverlies is het van klinisch belang, onderscheid tussen deze twee soorten slechthorendheid te kunnen maken. In de hersenstamaudiometrie is de positie van de "latency-Level curve" (l(L) curve) van de vijfde piek uit het hersenstam responsiepatroon ten opzicht van de referentiecurve voor normaalhorenden het belangrijkste instrument.
Dit was aanleiding om de meetfout van de l(L) curve te bestuderen. Met een test-retest experiment (hoofdstuk III) werd aangetoond dat de meetfout van de latentie van piek V toeneemt van ongeveer 0.1 ms bij hoge stimulatieniveaus tot rond 0.2 ms in de buurt van de drempel. Daar voor de diagnose en het vervolgen van conductieve gehoorverliezen de horizontale verplaatsing van de l(L) curve (in dB) van belang is, werden de meetonnauwkeurigheden van de latenties (in ms) omgezet in meetonnauwkeurigheden in niveau (in dB). Voor de lange latenties blijkt de onnauwkeurigheid in niveau het kleinst te zijn: <4 dB. Voor latenties korter dan 6 ms neemt de onnauwkeurigheid in niveau sterk toe tot meer dan 13 dB (hoofdstuk III, fig.1). Daarom werd het gedeelte van de curves met latenties onder de 6 ms uitgesloten bij verdere berekeningen van de horizontale verplaatsing van de l(L) curve in de hoofdstukken IV tot en met VI.

Voor het maken van onderscheid tussen de bestudeerde typen gehoorverlies werden drie aspecten van de positie van de l(L) curve onderzocht: de drempel, de horizontale verschuiving van de l(L) curve en van diens eerste afgeleide ten opzichte van hun referentiecurven. Deze drie aspecten van de l(L) curve werden gecombineerd tot lineaire "classificatie"-vergelijkingen met behulp van discriminant analyse. Genoemde procedure blijkt een bruikbare methode op te leveren voor het onderscheid tussen cochleair gehoorverlies en gehoorverliezen met een conductieve component. De hersenstam-classificatie " cochleair gehoorverlies" is in 86% van de gevallen in overeenstemming met het toonaudiogram. De hersenstam-diagnose "conductief verlies" wijst terecht een conductieve component in het gehoorverlies aan in 100% van de gevallen en de hersenstam-diagnose "gemengd verlies" doet dit in 86% (hoofdstuk V, tabel III).

Bij kinderen, die zonder sedatie of narcose onderzocht worden, kan in 15% van de gevallen geen drempel gemeten worden vanwege onrust van de patiënt. Teneinde na te gaan in hoeverre de methode toch toepasbaar is bij dergelijke patiënten, werd deze situatie gesimuleerd bij volwassen patiënten door gerandomiseerd de laag-niveau gedeeltes van de l(L) curves te verwijderen. Na analyse van de aldus ontstane verkorte curves (dus ook zonder drempel gegevens) werden grotendeels overeenkomstige resultaten gevonden als beschreven in de vorige alinea (hoofdstuk

VI. tabel IV). De hersenstam-diagnose "normaal gehoor" sluit een conductief verlies correct uit in 98% van de gevallen en de hersenstam-diagnose "cochleair verlies" doet dit in 79%. De hersenstam-diagnose "geleidingsverlies" voorspelt een geleidingscomonent in het verlies in 94% van de gevallen en dit geldt voor de hersenstam-diagnose "gemengd verlies" in 90%. Zonder de drempel kan echter geen goed onderscheid worden gemaakt tussen cochleair verlies en normaal gehoor.

We kunnen concluderen, dat hersenstamaudiometrie, met of zonder drempelbepaling, een nuttig instrument is voor de identificatie van een geleidingscomponent in een gehoorverlies. In de klinische praktijk betekent dit dat de hersenstam-diagnose "geleidingsverlies" of "gemengd verlies" een indicatie is voor verder onderzoek en behandeling van middenoorpathologie. Vanwege het matige onderscheid tussen zuiver geleidings- en gemengd verlies moeten we op onze hoede zijn voor een overblijvend cochleair verlies na behandeling van het geleidingsverlies. In geval van twijfel moet audiometrie herhaald worden. Verder kan geconcludeerd worden, dat de hersenstamdiagnose "cochleair verlies" zeer betrouwbaar is, mits de responsedrempel gemeten kan worden. In die gevallen is de gebruikelijke behandeling en begeleiding die hoort bij een dergelijke diagnose aangewezen zonder verder uitstel. Wanneer de drempel niet gemeten kan worden, is het alleen mogelijk een geleidingsverlies uit te sluiten. Als dat gebeurd is, is herhaling van het onderzoek onder narcose of met sedatie de logische volgende stap.

De klinische diagnose is altijd gebaseerd op meer informatie dan die door hersenstamaudiometrie alleen. Combinatie met een goede anamnese, KNO-onderzoek en tympanometrie blijft natuurlijk onmisbaar voor een optimale klinische beoordeling en besluitvorming. De evaluatie van de betrouwbaarheid van dergelijke gecombineerde klinische gegevens valt echter buiten het kader van dit proefschrift. De hier beschreven resultaten geven wel een aanwijzing omtrent het gewicht van hersenstamaudiometrie in deze besluitvorming.

Curriculum vitae

Frank van der Drift werd geboren op 21 december 1954 te Den Haag. In 1973 behaalde hij het eindexamen gymnasium β aan het gymnasium Sorghvliet te Den Haag. Het artsexamen werd afgelegd in 1980. In 1981 begon hij zijn opleiding in de keel-, neus- en oorheelkunde in het Academisch Ziekenhuis Dijkzigt te Rotterdam onder leiding van prof. Dr. P.C. de Jong en later van prof. Dr. C.D.A. Verwoerd. In 1985 werd hij ingeschreven in het specialistenregister. Momenteel is hij gevestigd als keel-, neus- en oorarts in het Diakonessenhuis Refaja te Dordrecht, in samenwerking met R.J. Visser en Jhr. Dr. H.E. Witsen Elias.