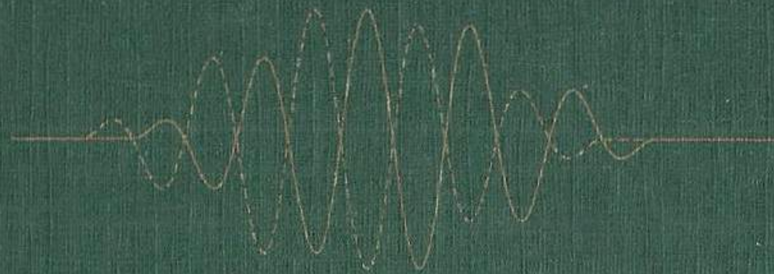
CANCELLATION AND EVOKED POTENTIALS — E. H. J. F. Boezeman

THE ESTIMATION OF THE BONE AND AIR CONDUCTION THRESHOLDS USING BRAINSTEM AUDITORY EVOKED POTENTIALS AND CANCELLATION TECHNIQUES

AN EXPERIMENTAL AND CLINICAL STUDY



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VRIJE UNIVERSITEIT TE AMSTERDAM

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ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van
doctor in de geneeskunde
aan de Vrije Universiteit te Amsterdam,
op gezag van de rector magnificus
dr. P.J.D. Drenth,
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door

EDUARD HENRI JAN FELIX BOEZEMAN
geboren te Hulst

Academische Pers
Amsterdam

Promotor: Prof. dr S.L. Visser
Copromotor: Dr T.S. Kapteyn
Referent: Prof. dr L. Feenstra

Aan Yvonne, Edmée en Emily

VOORWOORD

Dit proefschrift is tot stand gekomen door de bijdrage van velen. Ik maak graag gebruik van de gelegenheid een aantal mensen te bedanken.

Dit proefschrift is bewerkt in de afdeling klinische neurophysiologie (hoofd: Prof.Dr S.L.Visser) en de afdeling klinische audiologie (hoofd: Dr T.S.Kapteyn) van de Vrije Universiteit te Amsterdam.

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Prof.Dr J.J.Eggermont, zijnde een autoriteit op dit gebied van onderzoek, heeft al in een vroeg stadium de zin van de onzin gescheiden in eerdere versies van dit manuscript. Hij heeft daarmede de realisatie van dit proefschrift en het daaruit voortvloeiende vijftal publicaties in een niet onaanzienlijke mate bevorderd.

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CHAPTER 1

Introduction and Problem Definition

Introduction

The assessment of hearing loss, using audiological tests currently available, particularly requires the verbal cooperation and awareness of the patients concerned. Therefore the value of this information depends a great deal on the patient's mental state, which might be unfavorable during a test session, for instance when testing psycho-defective patients. It is important to assess hearing impairment in such a group as it might have therapeutic implications. Searching for objective and non-invasive methods not relying on the patient's frame of mind gave rise to this study. One of these methods is the brainstem auditory evoked potential. This measurement concerns the recording of event-related potentials from the human scalp evoked by auditory stimulation, the value of which has recently been testified to in many publications. It forms in addition to electrocochleography a powerful instrument to assess hearing impairment in a neurophysiological way.

In clinical audiology it is important to have sufficient knowledge of the hearing thresholds of the bone and air conduction system. A possible dissemblance in favor of the bone conduction system indicates a type of hearing loss situated in the middle ear, which may be improved by treatment. Brainstem potentials evoked by a brief signal presented to the earphone which refers to an air conducted transmission of the signal, have been thoroughly investigated. On the other hand, brainstem potentials evoked by bone conducted signals have hardly been investigated and will form, in conjunction with air conducted signals, an objective tool to differentiate conductive from sensorineural lesions. The possibilities and clinical applications of brainstem potentials evoked by bone conducted signals were therefore investigated in this study.

Any dissimilarity between the bone and the air conduction system can also be demonstrated by the cancellation technique. This psychophysical method is very sensitive in equalising two sinusoidal signals having the same frequency, which are transmitted simultaneously to one detector. By using the human ear as a zero detector, the air conducted signal can be related to the bone conducted signal. Subsequently this method can be used for relating the bone and air conducted perception to suprathreshold level. Although the adjustment has to be accomplished by the subject themselves, the correctness of this adjustment can be verified using the brainstem potential technique with air conducted stimulation. We have investigated the clinical applications of this method. Cancellation also supplies the phase relationship between the two signals. This will provide insight on the phase angle existing for the two identical signals being transmitted simultaneously via bone and air conduction channels.

General problem definition

In this study a number of topics are investigated and discussed, which are set successively in the following:

-The conditions for recording reliable and comparable brainstem potentials evoked by bone and air conducted signals. To establish the relation between the latencies of both responses corresponding to the audiometric hearing thresholds of these signals.

-The effects and limitations in the application of masking noise in brainstem auditory evoked potentials.

-The conditions for using the cancellation technique with continuous pure tones in subjects with normal hearing. To establish the intensity and phase relationship between the bone and air conducted signal at the point of cancellation.

-The verification of the point of cancellation in patients with hearing loss using the brainstem potential technique.

-The diagnostic clinical applications of the cancellation

technique in addition to the brainstem potential technique investigated in patients with hearing loss before and after treatment. To show the prediction capabilities of the cancellation method as well as evoked responses for the assessment of hearing loss compared to pure tone audiometry.

-The conditions for using the cancellation technique with impulse signals in subjects with normal hearing. To show the phase relation between bone and air conducted signals. In addition to establishing this relationship objectively with the brainstem potential technique.

The results of our study have been reported in separate articles and this study consists of an extended version of these reports. Each of the following chapters, except chapter 2, will consider successively one or more questions mentioned before. Chapter 2 has been written to give essential information on the topics investigated. Chapter 8 contains a summary of this study, in addition with a full Dutch translation, followed by a glossary.

CHAPTER 2

Review of the Literature

Classification of the Chapter

The application of brainstem auditory evoked potentials (BAEP) has made very remarkable progress during the past few years. The literature concerning this method is therefore widespread and is still increasing. The following chapter will therefore not comprise an all-inclusive survey of the literature related to evoked potentials. On the other hand it is felt that a survey discussing several parameters which have been selected on the basis of literature might be useful as an introduction to the topics studied. This chapter will therefore supply essential information on the technique of recording auditory brainstem evoked potentials in humans. It will highlight the developments and insights up to the present regarding the origins of these potentials, the normal values, the stimulus and the recording parameters. Finally, special attention has been given to the application of brainstem evoked potentials in clinical audiology as introduced up to now for the detection of hearing disorders. The literature and development related to the cancellation technique will not be reviewed in this chapter but in the chapters concerned. The following points will be discussed successively;

Historical introduction

Basic principles of brainstem auditory evoked potentials

Origin of the potentials

Normal values

Stimulus parameters

Recording parameters

Applications in hearing disorders

Conclusions

Historical introduction

The discovery of the spontaneous electric activity in the animal brain by Caton (1875) was the initial starting point for exploring the sensory evoked potentials. Seeking for responses to sensory stimuli, Caton found incidental electric fluctuations in his recordings from the rabbit's scalp. In fact, the story of evoked potentials ante-dated the processing of electrical cerebral activity in humans as discovered by Berger in 1929. From that time on human cortical electric responses to sensory stimuli were noticed by several investigators in a more general way, e.g. blocking of the alpha rhythm by opening of the eyes (Davis 1939). Searching for more specified potentials evoked by different kinds of stimuli, researchers could give essential information on specified neural pathways in the human brain. However, the technique was fraught with technical problems, for the potentials evoked were easily masked, owing to their low amplitudes, and by spontaneous electric cortical activity and other artifacts of biological and non-biological nature. A slight advance was made in improving the signal to noise ratio by superposition of cathode ray tracings. The range of this improvement was limited until the discovery of the averaging computer by Dawson in 1951. The advancement of this technical device at that time actually gave rise to a neurophysiological boom both in research and application of evoked potentials in clinical practice. The event related potentials recorded from the human scalp could now readily be extracted by summating the response and the averaging of background activity. Considering the development of auditory brainstem evoked potentials, Sohmer and Feinmesser (1967) recorded these potentials using an earlobe electrode referenced to the vertex in an attempt to find a non-surgical technique for evaluating the cochlear nerve action potential. This technique can be considered as a "far field" response. At that time also the method of the "near field" response was

introduced by placing an electrode in the ear canal (Yoshie et al. 1967). Other researchers used a transtympanic electrode positioned on the promontory (Portmann, Aran and LeBert 1968) which latter method is now widely known as electrocochleography. Besides the recording of the potential from the cochlear nerve, the so-called N I, Sohmer and Feinmesser also observed some negative earlobe waves extending out to a few milliseconds after the starting point of the click stimulus used. It remained, however, for Jewett (1970) to give a definite desciption of these potentials following the action potential of the cochlear nerve in the brainstem response. Jewett worked independently on the basis of animal research and later on with his colleagues Romano (1970) and Williston (1971) on the basis of human research. This method is now the most widely used test for estimating hearing thresholds by electric response audiometry and has completed the audiometric methods for the assessment of hearing in both infants and children. It also provides a secure estimate of the function of central auditory pathways located in the brainstem. Therefore it has become accepted in clinical neurology, as it can provide evidence of brainstem dysfunction due to tumors, multiple sclerosis or other pathological conditions.

Basic principles of the brainstem auditory evoked potentials

An orderly sequence of 6 or 7 low amplitude potentials, spaced about 1 msec apart can be recorded from scalp electrodes in human subjects. These potentials arise in the initial 10 msec following the onset of brief time-locked transient signals (fig.1) (page 22). These 7 small vertex-positive and vertex-negative wavelets are superimposed on a slow positive (around 5 to 6 msec) and negative potential (around 8 to 10 msec). These early potentials have such short latencies that they can not represent either neural events at the level of the cerebral cortex or myogenic responses mediated through brainstem reflex arcs.

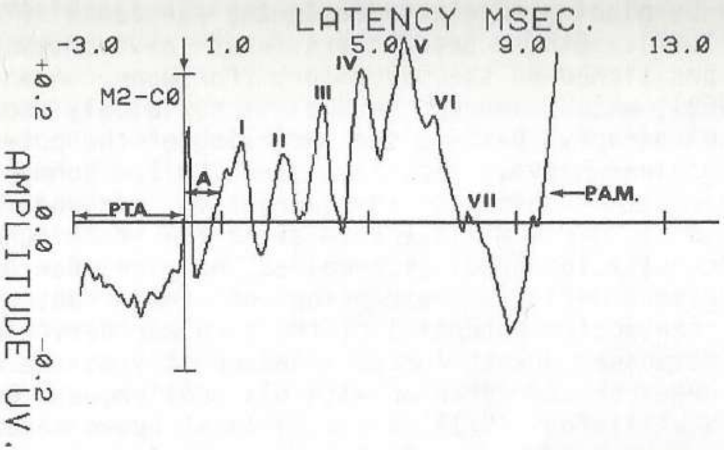

Fig.1. An example of a normal far field recording from the right mastoid (M2) to the vertex (CO) of short latency auditory evoked potentials. The successive waves are labeled with Roman numerals according to Jewett's convention. Vertex positivity is upwards. The response is the average of 2000 click stimuli passed to the right ear at a rate of 10/sec. Stimulus intensity is 70 dB SPL. P.T.A., pre-trigger analysis of the ongoing EEG; A, artefact (trigger + stimulus); P.A.M., post auricular muscle response.

The potentials are thought to be the "far field" reflections of electrical events, originating in the auditory pathways during its ascending course through the brainstem. The response to a single stimulus is of low voltage (less than 1μV) and is not discernible against random background EEG activity and muscle tension. However, if a large number of sound stimuli is presented and the response of the brain has been averaged by a computer, the brainstem auditory evoked potential will become more pronounced. Usually 1.000 to 2.000 stimuli are necessary to elicit a clear defined response. The stimulus normally used is a 0.1 msec click presented to a subject at a constant rate usually offered via a set of earphones. The intensity of the stimulus is kept constant and normally expressed in dB SL (sensation level), i.e., the dB level above the hearing threshold of that subject. The cerebral activity comprising cortical and

evoked potentials is recorded by a pair of standard EEG electrodes. One electrode is placed on the vertex (EEG position Co), the second electrode over the mastoid of the side being tested and the ground electrode on the scalp or on a non-cephalic position. These electrodes are further connected to electromagnetically shielded leads which lead respectively to the non-inverting and inverting input of the pre-amplifier. The processing system consists further of an amplifier normally built-in with a high and low pass filter device and then wired to the averager connected to a write-out system.The response write-out concerning polarity is still disputed. The normal convention in electroencephalography prescribes vertex negative up (Barlow et al.1974). Most data prevailing in literature dealing with BAEP are based on a vertex positive up convention, so we have plotted the response in this manner. The waves distinguished are labeled to Jewett's convention (1971) using roman numerals I up to VII. In literature another convention can be found using arabic numerals as introduced by Lev and Sohmer (1972). In this study we will restrict ourselves to Jewett's convention. A more detailed description of the wave forms will be discussed further on.

Origin of the potentials

Each of the waves distinguished represents electric activity generated by anatomical structures located in the brainstem. The generators of these evoked potentials have been disputed during the past few years. The anatomical structures giving rise to these potentials could only be disclosed by relating the surface recordings to those obtained from the depth-electrodes, i.e., during intracranial operations and also by studying the effect of brain lesions on these surface recordings. Consequently another controversy arose as to the origins of each of these scalp recorded potentials. Do they represent electric activity generated by separate distinct anatomical locations in the human brain or are they an addition of overlapping fields generated by several different anatomical structures. This issue was further entangled with the question as to whether these potentials were derived from post-synaptic potentials (grey matter) or from synchronized action potentials conducted by fiber tracts (white matter). Wave I is the only wave in the response of which its origin in human beings is now fully established. It represents the far field activity of the cochlear nerve. This was accomplished by recording directly the compound action potentials from the exposed cochlear nerve in patients undergoing neuro-surgical operations for cranial nerve dysfunction (Møller et al.1981, Hashimoto et al.1981 and Spire et al.1982). Placing the recording electrode on the nerve near the porus acousticus in the meatus internus as far as possible, the latency of the action potential obtained corresponded with the latency of wave I as observed in the brainstem response recorded simultaneously. These findings were in agreement with previous findings, i.e., that the latency of wave I in the brainstem response is similar to that of the compound action potential as can be recorded near the round window through electrocochleography (Don and Eggermont 1978). Thus wave I may be regarded as the earliest far field reflection of synchronized electric potentials generated from the most distal portion of the cochlear nerve. Knowledge considering the origin of wave II in the brainstem response has been gathered likewise. The origin of the neural generator giving rise to wave II in the brainstem response was assumed to be the cochlear nucleus only, which is located near the entry of the auditory nerve in the brainstem. That opinion has been partly revised recently due to the results obtained from intercranial recordings (Møller 1981). These results showed that wave II may arise from the proximal intercranial part of the cochlear nerve. This finding was supported by recent clinical evidence, that in cases of complete brainstem necrosis, the second wave is preserved (Stockard et al 1980). Another point giving support to this opinion took its rise from recordings of brainstem responses observed in children in which the second wave is difficult to identify. This could be explained by fusion of wave I and wave II owing to the shorter length of the auditory nerve in children compared to its length in adults (Salamy et al.1975). Finally Hashimoto et al. (1981) showed in their solid study, carried out in human beings undergoing intercranial operations, that wave II represented the far

field reflections of electrical events generated in the cochlear nerve as well as in the pons.The exact location of the neural generator positioned in the lower brainstem giving rise to wave II is still imprecise, but may involve the cochlear nucleus and the trapezoid body. These findings concerning the origins of wave I and wave II in humans coincide with the findings shown in lesion studies in cats by Buchwald and Huang (1975) and later by Achor and Starr (1980,I,II). Outlining the origins of the remaining wavelets in the response, much knowledge had been contributed by the analysis of changes in the brainstem response pattern in patients with brainstem lesions (Sohmer et al.1974; Starr and Achor 1975; Starr and Hamilton 1976; Stockard et al. 1977; Stockard and Rossiter 1977). According to these authors wave III has been regarded as the electric event generated in the superior olivary complex, whereas wave IV and wave V have been considered the electric events generated in the lateral lemniscus and colliculus inferior respectively. Recently results of depth recordings in humans from electrodes aimed at the close vicinity of the colliculus inferior were reported. Thereby was shown that the latency of the potential near field recorded is somewhat more delayed (0.5-1 msec) than wave V being far field recorded from the scalp simultaneously. Thus wave V in the far field response probably coincides with the preceding serial linked anatomical structures of the colliculus inferior in the brainstem,i.e.,the lateral lemniscus (Møller and Jannetta 1982). However, this finding is not quite in agreement with results of other intercranial recordings carried out, which strongly suggest that wave V originates from the colliculus inferior (Hashimoto 1981). Reports about the generator loci giving rise to wave VI and wave VII are infrequent. Stockard and Rossiter (1977) observed abnormality of wave VI corresponding with an anatomical lesion in the medial geniculate bodies (thalamus). The origin of wave VII is as yet not fully understood but it is perhaps connected to the geniculo-cortical radiations as put forward by Goff (1978). Another wave might be observed in the brainstem response having a latency of about 10-15 msec is the so-called post auricular muscle response (fig 1). Its presence is inconstant and changeable in normal subjects, as it is related to basal muscular scalp activity. On the other hand the averaged latency is fairly constant, provided that recording is performed from both mastoids using a fixed filter bandwidth. The presence of a recognizable response could then be used for determining the auditory threshold regardless whether this response comprises neurogenic or myogenic components as shown by Thornton (1975). The variability of this response is less near threshold using low intensity intensity levels. This is probably related to neurogenic components in the response, whereas high intensity levels result in more myogenic components associated with less stable responses and higher variability. Nevertheless not much attention has since been paid to its applications in clinical audiology for the estimation of hearing thresholds. Summarizing the opinions already established for the origins of the waves designated are, that on one hand one wave may originate from more than one nucleus or fiber tract and on the other hand both anatomical structures mentioned may contribute to more than one wave (Britt and Rossi 1980; Rossi and Britt 1980). There is no strict one-to-one correspondence between the different anatomic loci. To date some correspondence is generally accepted for clinical use of these evoked potentials, stating that wave I, wave II and wave III represent the successive activation of peripheral, ponto-medullar and pontine portions of the auditory pathway and that wave IV and wave V represent the activation of the pontine and midbrain portions of the ascending auditory pathway. However, it must be taken into account that a traveling wave delay exists along the cochlear partition which amounts up to 4 msec (to the 500 Hz region). This can easily interfere with the delay along the neural axis (Eggermont and Don 1982).

Normal values

In fig.1, the absolute peak latencies (PLs) of the waves designated can be calculated from the onset of the transient stimulus using digital cursors. PLs can therefore be calculated to the nearest 10- 50 μsec depending on the dwell

time of the averager used. One can also use the latency between the peaks (interpeak latencies:IPLs) of waves I and III as an indirect measure of conduction in the extra-axial and ponto-medullary segments of the auditory pathway. The IPL III-V can be used as a measure of conduction of more rostral pontine and more caudal segments of the pathway. Consequently the IPL I-V deals with the conduction of both pathways. One must consider that in using IPLs for clinical practice, the identification of peak I is important. It is the electrophysiologic benchmark from where the central conduction times are assessed. For these PLs and IPLs there is a low inter-individual, but particularly a low individual variability if the same recording conditions are met. This makes them very useful in clinical practice as shown by several authors (Hecox and Galambos 1974; Thornton 1975; Stockard et al.1979; McClelland and McCrea 1979; Edwards et al.1981). An aspect stressing this finding even more is, that the PLs and IPLs remain unaffected to most non-specific central nervous depressants, e.g. barbiturates, benzodiazepines and during halothane anaesthesia. However, caution is demanded for drugs affecting specific neurotransmitter systems possibly involved with generation of these potentials, e.g. serotonine (Bhargava and McKean 1977) and acetylcholine (Bhargava et al.1978). More assets gaining their diagnostic capabilities employing PLs and IPLs are their resistance to fluctuations in arousal and to any long-term habituation (Salamy and McKean 1977). Another point which should be comtemplated is the effect of body temperature, which might delay the PLs and therefore may alter the IPLs in magnitudes of 0.25-0.45 msec/ $^{\circ}$C in patients prone to develop hypothermia, i.e., below an esophageal temperature of about 32°C (Stockard et al.1978; Kagha et al.1979). Hyperthermia may cause the reverse effects. Many reports have been published about the influence of age on the IPLs. The influence of age must be considered when interpreting BAEPs. It has been established that below the age of 2-3 years, and especially in premature infants, the IPLs are prolonged relative to adult values (Schulman-Galambos and Galambos 1975;Salamy et al.1975;Starr et al.1977; Schulman-Galambos and Galambos 1977;Cox et al.1981). The prolongations of these IPLs presume to reflect the maturation of the auditory pathway in the brainstem. As seen among the results of these authors mentioned, the maturation of the brainstem manifests itself in exponentially (Eggermont 1983, in press) decreasing IPLs in magnitudes of 0.01-0.03 msec per week in the first year of live and a maximal shift of 0.4 msec in the 32-34 week conceptional age. This maturation phenomenon was also emphasized by Fujikawa and Weber (1977) and Salamy et al. (1978). They stated that newborns in comparison to older age groups showed slower recovery for their IPLs to increasing rate of stimulation. This finding emerged particularly for those waves (III and V) being representative of rostral brainstem activity. This is in agreement with the known caudo-rostral maturation of the brainstem which in this respect is probably related to the myelin composition along the auditory pathway (Rorke and Riggs 1969). Advancing age has also its implications on IPLs but is most likely related to hearing impairment for higher frequencies often met within older people. It results mainly in a shorter IPL I-III due to prolongation of wave I. The effects of gender on the PLs and IPLs have been grossly unappreciated during the historical development of BAEP. Females as shown now have significantly shorter PLs and IPLs than males (Beagley and Shelldrake 1978; Jerger and Hall 1980). This sex difference was also encountered in adults by McClelland and McCrea (1979), but not in pre-adolescents with normal hearing. They found that the PLs obtained in this group matched those which were observed in the adult female group. They suggest that the gender difference between males and females is acquired during adolescence. It has been assumed that a smaller pathway length in females from the cochlear nerve to the midbrain, resulting in reduced neural transmission time, could account for these effects. Amplitudes can also be considered in the response and are usually calculated from the positive peak of each wave to the following through, i.e., the negative peak of the wave involved. The amplitudes are small, ranging from 0.1 µV to 0.5 µV, of which wave V has usually the highest voltage (fig 1). However amplitudes have not been appreciated in clinical practice due to their high variability in contrast to PLs and IPLs. An approximation now commonly used is the

amplitude ratio of the waves IV/V:I. This ratio (normally>1) is not consistently affected by temperature, age and gender as Pls and IPLs are. The amplitudes in older people may show a decrease of about 0.05 µV compared to younger people and this is also gender dependent. The amplitudes of wave V in females may exceed those which are measured in males by amounts ranging from 0.080 µV in younger people to 0.120 µV in older people (Jerger and Hall 1980). Its inconsistency is increased even more compared to PLs and IPLs by audiogram shape and technical factors, i.e., processing, recording and stimulus parameters. Its clinical use has been investigated for detecting occult lesions in patients suffering from multiple sclerosis (Kjaer 1980; Robinson and Rudge 1980; Phraser et al. 1982) as well as in patients suffering from hearing loss (Møller and Blegvad 1976; Kavanagh and Beardsley 1979). Summarizing this presentation for these general non-pathological factors influencing BAEP, several requirements need to be met when gathering normal values for PLs, IPLs and amplitudes in the human brainstem response. One's own equipment should be used for collecting norms. It is preferable to have them for the major age groupes and for both sexes as well. Adopting norms from literature should be avoided, because small technical factors, i.e., stimulus and recording characteristics easily prevailing among the various laboratories cause considerable differences in the norms as shown in the following

Stimulus parameters.

-Stimulus mode

The amplitude of the brainstem response to binaural stimulation exceeds that which is monaurally evoked. This manifests itself in an increased IV/V:I ratio, because of the monaural contribution of wave I and the binaural contribution to waves IV and V. On the other hand no significant changes in latency values have been observed between the two different modes of stimulation (Peter and Mendel 1974; Ainslie and Boston 1980). Binaural stimulation should be avoided in clinical practice, because ipsilateral lesions whether neurologically or otologically defined, may be masked by the response derived from the unaffected side (Phraser and Gibson 1980). A further advantage can be obtained by separate left and right ear stimulation. Comparison of interaural asymmetries in IPL, which considered separately from each ear, may be judged as being within normal limits. This interaural difference between left and right ear stimulation is varying among laboratories as put forward by van Olphen (1983). Generally, the upper limit of this value is 0.4 msec, otherwise it may be suspect for neurological or otological disturbances. If monaural stimulation is performed, masking of the non-stimulated ear is important, particularly in subjects with severe interaural hearing asymmetries. Omission and sometimes failure in masking the better ear when stimulating the poorer ear, is capable of evoking BAEPs from the good ear by shadow hearing.

-Stimulus intensity-calibration

Several viewpoints have been given recently about calibration of intensity of brief stimuli as used in evoked response audiometry (Picton et al. 1981). This can be performed either physically or psychophysically. Using a symmetric signal like the sine wave form, the maximal peak-to-peak amplitude of the signal can be matched to the amplitude of a continuous tone of the same frequency. The acoustic condensation and rarefaction phase of the stimulus used, is then identical. The sound pressure level (dB SPL) can be measured easily. This calibration gets complicated when calibrating acoustic asymmetric wave forms commonly used, such as clicks, i.e. rectangular pulses. One possibility then is to calibrate the peak-to-peak amplitude of the acoustic wave form, which is asymmetric about the baseline and therefore asymmetric in its phase. Another approach involves the calibration of only the highest peak sound either located above or under the baseline apart from whether this concerns a rarefaction phase or a condensation phase. From a physiological point of view, Corti's organ reacts only to one phase, i.e. the peak rarefaction sound pressure (Kiang et al. 1965), so it may be advisable to calibrate the rarefaction phase of the stimulus. A practical

suggestion has been made by Davis (personal communication), stating that the use of clicks should be avoided and the use of tone bursts should be considered. Brief tone bursts of 4000 or 2000 Hz provide sufficient rapid onset to evoke potentials and the calibration of the stimulus intensity renders less difficulties. Another type of calibration is the psychophysical method. This bears upon the measurement of the average psycho-acoustic hearing threshold in a group of normal young adults for the particular brief stimulus being applied (dB HL). Since the perception for hearing depends on the duration of the stimuli used (Plomp and Bouman 1959; Dallos and Olsen 1964), the threshold of brief bursts is elevated compared to the threshold estimated by using a continuous tone of the same frequency. This elevated threshold for the brief stimulus being used may thus provide a reference for calibration of the stimulus intensity. One can also calibrate the intensity of the stimulus to each individual subject's threshold, i.e. sensation level (SL). However, caution is needed in relating SL intensities to the effective stimulus intensity in patients with hearing loss and recruitment. In contrast to the threshold procedure discussed above, one may also use the masked threshold procedure, i.e., estimating the detection threshold of the brief stimulus through a fixed noise intensity. A drawback using psychophysical calibration procedures for brief signals in evoked response audiometry generally is the fact that the perception of the stimulus and therefore its reference is related to its total duration. However, in BAEP the response acquired is related to the very onset of the stimulus, i.e., the rise time of the slope of the very first part of the stimulus ascending to its maximum sound pressure (Suzuki and Horiuchi 1981). In literature either the physical or the psychophysical routine has been followed, or both. A general reference has yet not been accepted. Perhaps as put forward by Arlinger (personal communication) one will accept as zero dB reference a certain click level passed through standardized earphones, which barely evokes an identifiable response in subjects with normal hearing. However, this latter approach may be impractical because threshold measurement depends critically on the residual noise level after averaging, which is not one and the same in subjects and therefore difficult to standardize.

-Stimulus intensity-latency relation

The underlying physiological processes giving rise to the latency-intensity relation observed both in BAEP and in electrocochleography is partly understood up till now. Basically, three cochlear processes are directly involved with the latency-intensity function. Firstly, it depends for a great deal on the traveling wave delay existing along the cochlear partition. This delay is related to which part of the cochlear partition is activated, and amounts to about 4 msec for apical regions (Eggermont and Don 1982). Furthermore, it involves a shift of the activity pattern toward the more basal parts of the cochlea of the dominant contributing regions to the BAEP response for clicks of increasing intensity. This implies, that the auditory fibers which contribute dominantly to the BAEP response, are activated earlier which will shorten the response latency (Don et al.1979; Eggermont and Don 1980).

Secondly, it is shown by findings in electrocochleography (Eggermont and Don 1982) as well as in BAEP (Parker and Thornton 1978), using narrow band responses, that traveling wave velocity increases toward the basal part of the cochlear partition. It is shown that this is accompanied by a gradual increase in the amount of synchronization of the fiber activity that contributes to the narrow band response with a higher central frequency. This increase of synchronization will increase the detectability of the BAEP. Another topic which is able to change the latency, concerns the synaptic delay existing at the junction between the hair cell and the cochlear nerve.

Thirdly, the response latency is modified by the onset of the stimulus (Hecox et al. 1976). It is not influenced by its offset, nor by its duration provided sufficient time is allowed for response recovery. Increase of the rise-time of the stimulus prolongs the response latency while the converse situation shortens it.

-Stimulus-repetition rate

Repetition rate has a marked influence on BAEP components. Systematic researches into its effects have been published after the final description of BAEP components given by Jewett and Williston (1971). Recent results on the basis of research in cats (Huang and Buchwald 1980) revealed that the near field recordings, taken from the cochlear nerve as well as from the cochlear nucleus, showed an identical amplitude decrement at rates exceeding 10/sec. These results could be considered as adaptation effects suggesting that rate effects in cats may be involved with more peripheral mechanisms in the auditory system. Probably it concerns synaps depression at the hair cell-cochlear nerve junction and perhaps this may also account for rate effects in human BAEP components. In humans this was confirmed by Thornton and Coleman (1975) showing that adaptation effects on amplitudes increased at higher rates of stimulation. They also found that the central nuclei in the brainstem showed less adaptation than that found at the periphery, strongly suggesting different adaptation mechanisms in the peripheral and central responses. Besides this, with regard to the amplitude of the human compound action potential of the cochlear nerve, Eggermont and Odenthal (1974) noticed increased adaptation at increasing intensities, particularly observed at high rates of stimulation. These changes in adaptation occurred at a certain intensity level, which correlated with the change-over point in the activity of two neural populations. The PLs in the human response are influenced to different degrees at different rates of stimulation (Hyde et al. 1976; Pratt and Sohmer 1976). The PL of wave I is hardly affected at higher rates of stimulation in contrast to its amplitude. For the successive waves there were more effects observed on the PLs, the effect being more pronounced for the later waves. The amplitude of the later waves were, in contrast to wave I, less affected than their PLs. Furthermore, Don et al. (1977) established in subjects with normal hearing that these latency shifts occurring at higher rates of stimulation were restricted to the monaural pathway and did not depend on binaural interaction from the central auditory nuclei in the lower brainstem. The adaptation effects observed in this study are therefore confined to be generated in time prior to the decussation where the pathways from the two ears interact in the generation of BAEP. This suggests a peripheral process being responsible. This opinion was also stressed by Starr and Brackmann (1979) in their study. They stimulated the remaining eight nerve fibers in patients with cochlear implants by means of electric current via an electrode located in the scala tympani. The PLs of the waves, evoked by electric stimulation, barely showed adaptation, i.e., prolongations of the PLs at increasing rates of stimulation. The same increase in rate resulted in a marked adaptation when auditory stimulation was employed. This finding supports that adaptation effects occurring at a rapid rate of stimulation are involved with cochlear processes. Speaking in terms of magnitude the PLs and IPLs and amplitude show no significant changes until the rate of the stimulus presentation exceeds 10/sec. The mean PL of wave V, being sensitive to increasing rates of stimulation, shows an increase of about at rates exceeding 30/sec up to 100/sec. The mean IPL I-V increases by approximately 0.1 msec for each 20/sec increase in repetition rate. Rapid rates of stimulation are also associated with an increased IV/V:I amplitude ratio because of the relative resistance of the amplitude of wave V to rapid stimulation (Stockard et al. 1978). The number of precise data concerning adaptation effects on the earlier waves generated in the brainstem are restricted. The cause can be found in the associated loss of BAEP resolution due to amplitude decrement especially arising in these earlier waves at fast repetition rates. Repetition rates have been investigated for their clinical use and they may serve as a tool for the assessment of the lower brainstem function in pathological conditions of different nature (Robinson and Rudge 1977; Hecox et al. 1979; Shanon et al. 1981).

-Stimulus-polarity

Stimulus polarity should be carefully controlled, i.e., the rising part of the stimulus used must start in a controlled phase. Rarefaction (R) stimuli are produced by initial

movement of the membrane of the headphone away from the tympanic membrane and condensation (C) stimuli results from initial displacement towards it. It has been established in animals (Kiang et al. 1965; Anatoli-Candela and Kiang 1978) that a given auditory neuron reacts only during the period when the basilar membrane is displaced towards the scala vestibuli, i.e., during the rarefaction phase of the acoustic sound wave. Many reports have been published during the past few years investigating the relationship between the brainstem response and the polarity of the stimulus. Several authors (Ornitz and Walter 1975; Coats and Martin 1977; J.J. Stockard et al. 1978; J.E. Stockard et al. 1979; J.J. Stockard et al. 1980; Picton et al. 1981) noticed that in humans the PL of wave V tended to be constant, while the PLs of the earlier waves tended to decrease with R stimuli and increase with C stimuli. The PLs differed consequently in these studies. As far as the amplitudes are concerned, wave I seems to be more pronounced with R stimuli. However, in contrast to these findings, neither Terkildsen et al. (1973), nor Rosenhamer et al. (1978) could find any significant difference in the response between a given polarity change, whereas Hughes et al. (1981) found the opposite results. Tvete and Haugsten (1981) reported that these studies were in conflict, because the acoustic wave form of the click stimulus used could be different to some extent and may account for the differences observed. They found, on the basis of animal research, that differences in PLs were more prominent at a given polarity change by using clicks with broad peaks in their acoustic wave forms than clicks with more rapid deflecting peaks in their acoustic wave forms. They also noted that pronounced shifts of PLs were more dependent on high intensity levels. This factor was not matched in those studies. Seen among the results published to date, there is general agreement about a considerable intra subjective and inter subjective variability occurring with a given polarity change. It is stressed that the PL of wave V shows little alteration at a given polarity change in contrast to the earlier waves. This was even more striking in newborns (Stockard et al. 1980). They assume a different cochlear origin for the generation of wave V being more mature than the origins giving rise to the earlier waves. This assumption could provide evidence that the BAEP components derive more from independently parallel pathways rather than from sequentially activated pathways in the brainstem. Another form of stimulation concerns the use of alternating the polarity of the stimulus being used, which minimizes electrical and stimulus artifacts. This may be an advantage, e.g. when using high intensity levels. The polarity of the stimulus used should be kept constant and one should generally prefer the rarefaction phase, for being the natural stimulus to the inner ear. In individual cases C or C/R clicks may be of use.

Recording parameters

-Electrode position

Many contributions concerning the appropriate electrode position and montage for recording BAEP have been achieved by means of mapping studies. These studies concerning the spatial scalp distribution and their phase relationships of evoked potential components were carried out with multiple electrode arrays. Recordings of evoked potentials were derived simultaneously from either referentially or differentially electrode montages. This topografical analysis thus yields information about evoked potential sources (Vaughan and Ritter 1970; Picton et al.1974; Goff 1978). Furthermore clinical findings attributed to the knowledge of appropriate electrode configurations. These findings suggested that in patients with known lateralised brainstem pathologies,abnormalities in the BAEP occurred only on the side of the lesion. Ipsilaterally recorded brainstem responses were mainly the result of neural activity generated on that side (Thornton 1975; Van Olphen et al. 1979; Shin et al. 1981). It is obvious that one should place one electrode on that scalp position which reflects the most far field activity from the auditory brainstem nuclei and fiber tracts. This has been proved to be the vertex (Picton et al. 1974; Terkildsen et al. 1974; Stockard et al. 1980). On the other hand controversy arose concerning the location of the reference electrode and its

linkage to the vertex electrode. An ideal reference position should be a neutral one, i.e., one the least affected by differences in potential over spatial location and over time during the recording of the far field activity from the active electrode. When such a reference is used, the activity picked-up over time by the active electrode can then be actually considered as real reflections of evoked amplitude changes rather than a complex sum of amplitude changes at both electrodes. Referential recordings with non-cephalic reference electrodes, e.g. located on the wrist, the ankle, the sternum and the neck have received much attention in this respect. Unfortunately the signal to noise ratio detoriates considerably when active and reference electrodes are spaced far apart on the body due to concurrent muscle activity at the reference site. On the other hand differential recordings between cephalic electrodes improve the signal to noise ratio, but initiate simultaneously complex wave form interactions between contributions picked-up by the cephalic electrodes. The reference electrode is then not neural, moreover the terms active and reference become meaningless since there is representation of the far field activity at both electrode positions. Changes in the position of cephalic electrodes will result therefore in complex latency, amplitude and wave form alterations for all BAEP components. Changing the position of the cephalic electrodes one may enhance one wave but diminish another. It has been observed that significant differences in the PLs, IPLs and amplitudes arise by changing the mastoid or earlobe electrode referenced to the vertex from ipsilateral to the side contralateral of acoustic stimulation (Stockard et al. 1978; Phraser and Gibson 1980; Parker 1981; Robinson and Rudge 1981). In the current literature it is now generally proposed that these differences are based on the fact that ipsi- and contralaterally auditory pathways are involved in the generation of BAEP. It becomes clearer in the light of anatomical findings that the ascending auditory pathways in animals (Buchwald and Huang 1975) and humans (Luxon 1981) comprises uncrossed and crossed fiber tracts. Consequently the PL and amplitude of a wave distinguished in the response primarily depends upon the propagation characteristics of the transmission path between the generator giving rise to a specified wave and the position of these recording electrodes. It depends in the second place upon the spatial orientation of activity of these generators with regard to these electrodes (Hubbard et al. 1969). The following recordings are now generally accepted as appropriate for resolution of BAEP components; from vertex (EEG position C_o) to the mastoid, or from C_o to the earlobe ipsilateral of acoustic stimulation. It is clear when taking notice of these data derived from literature, that one should apply the same recording characteristics throughout; but one is free to differ from this opinion in order to enhance a specified wave in the response by changing stimulus and recording parameters, as will further be discussed in the following.

-Identification of components

Wave V

Wave V is the strongest wave in the response with its maximum recorded at the vertex. It is recognised by a prominent positivity followed by a large, sharp negative deflection (fig.1). The PL of this characteristic wave form can often be recorded within 10-20 dB near the audiometric threshold of the stimulus used, while other waves have vanished in the noise. This feature facilitates the detection of wave V in the response recorded at supra threshold level because wave V is often not the arithmetical fifth positive wave being visible in the response. If wave V is barely recognised in pathological conditions simultaneous recording from the electrode (mastoid or earlobe) contralateral to acoustic stimulation might be useful. It then often shows an enhancement of this particular wave with a slightly prolonged latency compared to its ipsilateral measured latency.

Wave IV

From this wave different morphologic variants have been described (Chiappa et al. 1979). Wave IV often tends to fuse

with wave V in a complex manner. It is normal to have either: (1) separate peaks with equal or unequal amplitudes for wave IV and wave V respectively; (2) a skewed peak for wave IV appearing as a slight inflection on the rise slope of wave V, or conversely, wave V being visible as a slight inflection on the fall slope of a predominant wave IV; (3) a completely fused wave IV and V forming one broad wave. We also observed various wave forms in our study and some guidelines have been generally accepted for measuring the PL. If there is no clear inflection between wave IV and V because of partial fusion of these waves, a mid-point of the wave form is calculated and is regarded as its PL. In the case of total fusion of both waves the PL is calculated to the point of final inflection before the fall slope of wave V and is regarded as the PL of wave V. There is quite a high inter- and intrasubject variation in the morphology of this IV/V complex, having up to now no clinical significance. It is sometimes dependent on the polarity of the stimulus (Stockard et al. 1980). Recording simultaneously from the electrode contralateral to acoustic stimulation might resolve wave IV and wave V in the response, e.g. in a fused wave IV/V complex.

Wave III

This wave is thought to be a reflection of the first stage of bilateral innervation in the ascending auditory pathway, i.e. the superior olivary complex. It is after wave V the predominant wave observed in the response and it is most pronounced from ipsilateral recordings to acoustic stimulation. Contralateral recordings attenuates this wave with a decreased latency, probably due to more rapid conduction velocity of crossed pathways (Harrison and Howe 1979). Sometimes a bifid wave III is seen having no clinical significance and most likely related to the initial phase of the stimulus.

Wave II

It is generally held that wave II is equally recorded from electrodes ipsilateral and contralateral to acoustic stimulation. However, taking recordings contralaterally may favor its recognition as wave II is then preceded and followed by two attenuated peaks (I and III).

Wave I

There is no doubt that wave I is derived from the ipsilateral side as its positive deflection is not observed in contralateral recordings. This finding confirms the opinion of the auditory nerve being its origin. Increasing stimulus intensity and decreasing repetition rate of the stimulus are common procedures for enhancing wave I in the response. In the case of large stimulus artifacts, e.g. using high intensity levels, stimuli with alternating polarity can be useful. Another appropriate and more powerful method of resolving wave I is the application of an external auditory canal (EAC) reference electrode (Coats 1974). This device allows resolution of wave I even under most unfavorable conditions (Coats and Martin 1977). In conclusion we have confined ourselves as much as possible in this study to calculating the latencies of the successive waves from the ipsilateral recordings, i.e., the electrode montage ipsilateral to stimulation. When such a measurement failed, one of the above suggested procedures was followed (the EAC electrode was not employed).

Filter setting

Generally speaking, the design of an appropriate filter must meet two basic requirements. Firstly, the filter must operate efficiently in separating the signals of interest from the background noise. Secondly, the distortion introduced in the signal by the filter should have hardly any effect on the particular signal characteristics that are of interest. A specific recording of BAEP components implies a third important factor, i.e., the need of high and low pass filters as the background noise contains a broader spectrum than the response wave form. Thus the spectral content of the response wave form determines the cut-off settings of these filters. Spectral analysis of BAEP components, provided that a proper analysis window length is

used, shows that most of the energy to the total power is contained in the band between 50-100 Hz whenever click or other high frequency stimuli are used (Elberling 1979). This low frequency spectrum is considerably reduced when the corresponding spontaneous brain activity is subtracted from the response spectrum. The dominant frequency contribution is then found in the 500-2500 Hz bandwidth with a maximum power in the 800-1200 Hz frequency range (Laukli and Mair 1981). Varying the spectral content of the stimulus at a fixed intensity produced no significant changes in the spectral content of the response wave form, except for the 500 Hz stimulus (Suzuki and Horiuchi 1977). Considering the frequency domain of BAEP components using high frequency stimuli, the cut-off frequency for the high pass filter is 100 Hz or lower (roll-off of maximal 12 dB/octave) for removing low frequency components. The cut-off frequency of the low pass filter is usually set at 3 000 Hz (roll-off of maximal 12 dB/octave) for removing high frequency noise (Jewett and Williston 1971; Stockard et al. 1978). When using low frequency stimuli (e.g. 500 Hz) in audiometric work the cut-off frequency of the high pass filter is usually set at 30 Hz. A special remark concerns the type of filtering. One usually employs analogue high and low pass filters. These filters produce to some extent phase shifts of the waves concerned and therefore time shifts of the PLs. On the other hand digital filtering introduces hardly any phase shift because they attenuate extraneous spectral components more efficiently, which finally results in a shorter recording time. Digital filtering for these reasons seems to be superior to analogue filtering and most promising as shown in comparative studies (Møller 1980; Boston and Ainslie 1980). We have confined ourselves to analogue filtering with the accustomed bandwidth.

Applications in hearing disorders

The most striking characteristic of BAEP components is their latency sensitivity to the intensity of the stimulus. The PLs of the waves distinguished increase with decreasing intensities and also conversely. This can be considered as successive reflections of cochlear activity. These features have finally proved their strength in clinical audiology for detecting peripheral hearing losses. The use of wave V is therefore recommended for its recognition near threshold. The PL of wave V in the response is determined by stimulus parameters, middle ear function, cochlear processes and the conduction time in the auditory pathways in the brainstem (Eggermont 1983). Its cochlear determinants are dependent on the delay of the traveling wave to reach a responsive area of the basilair membrane. It has been suggested in studies using masking techniques that wave V derives from a more extensive length of the cochlear partition and the other earlier waves from more basal regions (Don and Eggermont 1978). The final determinant of the PL of wave V concerns the central transmission time from the cochlear nerve (wave I) to the generator of wave V in the brainstem. This delay (about 4 msec) is quite stable in individuals, provided that the brainstem function is normal and therefore justifies using wave V in the detection of hearing loss. The IPLs can be considered as separate from the cochlear effects and therefore being useful in detection of retrocochlear disorders giving rise to hearing impairment. If the thresholds as indicated by evoked potential techniques are elevated, further data about the kind of auditory impairment are necessary. Some characteristics of these latency-intensity relations have been established so far in the response. They may serve as guidelines as will be shown for splitting hearing disorders in conductive and sensorineural types, the latter consisting of cochlear and retrocochlear disorders.

Conductive hearing loss

With a pure conductive hearing loss the sound energy reaching the cochlea by means of a headphone is reduced. The latency is then a function of the sensation level of the stimulus, the audiometric shape, and of the changed middle ear transfer function which will modify the effective spectrum of the stimulus (Picton et al. 1981). The latency-intensity relations, i.e., the PLs of the successive waves are shifted to increased latency levels by amounts corresponding to the conductive loss (Galambos and Hecox

1978; Gerull et al. 1978). The IPL III-V remains unaltered, but the IPLs I-III and I-V are slightly reduced. These latter effects are understood on the basis of traveling wave delay (Eggermont and Odenthal 1974; Elberling 1974; Eggermont and Don 1982). At low intensity levels the effective click spectrum is determined in normal ears by the outer ear canal and the middle ear transfer function. At high intensity levels this is still so but more basal parts of the cochlear partition are activated which will shorten the PL of wave I. Excluding conductive loss is important, when hearing impairment is dealt with, as it prolongs the PL of wave V considerably and is therefore able to mimic a retrocochlear disorder (Clemis and McGee 1979). A correction factor in milliseconds could be useful in such cases to compensate for the delayed latency shift as put forward in a preliminary study by Borg (1981). A different method, being straightforward for showing a conductive loss, is tympanometry. In that respect a second neurophysiological approach concerns the normal latency-intensity function attained with bone conducted stimuli. With this approach attempts are not very successful so far.

Cochlear hearing loss

With a pure cochlear hearing loss the PLs of the successive waves are dependent on the intensity of the stimulus as well as on the remaining responsive areas of the basilar membrane. The sound energy detected in the cochlea is dependent on the time the traveling wave needs to reach a responsive area. In cochlear hearing loss the affected responsive areas may involve either a low frequency loss or a high frequency loss, or both. The contributions in the hearing impairment of these spectral deficits may be different in each case. This will affect the PLs in a different manner considering that BAEP components are derived from more basal portions in the cochlea that subserve the perception of high frequency sounds being the most vulnerable part for pathology. Wave V latency increments foot up to about 0.1 msec for each 10 dB hearing loss above 40-50 dB HL at 4 kHz (Brackmann and Selters 1979; Rosenhamer et al. 1981). It has been stressed in this respect that in patients suffering from sensory (cochlear) hearing loss, the PL of wave V was more delayed in high frequency hearing loss in contrast to the findings in low frequency hearing loss. In fact the PL values and amplitudes,obtained in response to clicks, as observed in low frequency hearing loss as well as in flat cochlear hearing loss could approach normal limits (Yamada et al. 1975; Galambos and Hecox 1978). This observation makes distinction from flat conductive hearing losses possible (parallel shifted latency-intensity function in that case) but offers serious problems when dealing with mixed sensory hearing losses or with high-frequency sensory hearing losses. The latency/amplitude-intensity functions of narrow band responses for tone burst stimulation instead of clicks may eliminate some of these problems (Eggermont 1983).

Another point one should give attention to is the presence of recruitment which often occurs in patients with sensory hearing loss. It considers the abnormally rapid increase in loudness of an acoustic signal. Because of its cochlear origin it should be measurable with electrocochleography and/or BAEP. Growth of loudness has been related theoretically to the driven spike rate of all auditory nerve fibers (Goldstein 1974). Loudness depends on the duration of the stimulus which is in fact a sustained neural activity. The amplitude of wave V or wave I relies on the onset of the stimulus as discussed. Smith and Zwislocki (1975) showed that the ratio between onset neural activity and steady state neural activity is constant over a wide intensity range. In this way loudness can be related to the amplitude of the compound action potential (AP). The clinical implications has proved to be very useful, despite the relation between growth of loudness and growth of AP amplitude remains unclear. In recruiting ears, using electrocochleography, the slope of the AP amplitude-intensity function is steeper that that found in normal ears (Eggermont 1983). Using the latency-intensity function of wave I or wave V for the prediction of recruitment, no significant clinical proof has been established. As discussed, latency measurements are more directly involved with stimulus parameters, audiometric

shape, and the transfer function of the middle ear.

Retrocochlear disorders

This kind of hearing impairment involves disorders affecting the cochlear nerve, e.g. pontine angle tumours, or lesions from more central localized auditory pathways. When sensorineural hearing loss is dealt with it is important to verify whether it is cochlear or retrocochlear in origin and then to establish the false positive and false negative rate of a given result. Some solid studies have been devoted to establishing its existence by means of BAEP applied to a group of patients involving surgical confirmed tumorous lesions of the cochlear nerve and non-tumorous lesions. This practice yields the "hit" percentage of a certain test and therefore the false negative findings (Selters and Brackmann 1977; Clemis and Mitchell 1977; Rosenhamer et al. 1977; Hyde and Blair 1981; Eggermont et al. 1980; Eggermont 1983, in press). A preferred measure appeared to be the inter-aural latency difference (ILD) of wave V. This measure is based on a normal reference in each case, i.e., the ear contralateral to the affected one. If not, false positive findings could easily interfere. Furthermore a correction factor was introduced to allow for any latency increase due to high-frequency loss in the affected ear. By doing so the false negative rate was about 9% and the false positive rate about 10%. Sources of error resulting in false negative findings were posterior fossa tumours not directly touching the cochlear nerve and, as exception, bilateral cochlear nerve tumours (the PL of wave V is then equally prolonged at both stimulated sides). Recruitment phenomenon in one sided sensory hearing loss may also contribute in this respect. False positive findings were related mainly to conductive losses and in lesser degrees to vascular or traumatic lesions. Diminishing the influence of peripheral effects and so the presence of false positive findings has been sought in the additional application of using the interaural difference of the I-V interval. The presence of a recognizable wave I and V is therefore needed, a criterion which is mostly not fulfilled in these cases whereby BAEP is used solely. In that respect the additional use of electrocochleography has been employed for resolving wave I (Eggermont et al. 1980). This set-up in that specific study yields to a score of 95% for detecting tumours and 95% for detecting peripheral losses, so diminishing the number of false positive findings.

Frequency specificity

The application of BAEP in clinical audiology has mainly considered the assessment of auditory thresholds so far by using clicks. Assessing thresholds at any particular frequency could complete the diagnostic capabilities of BAEP. Owing to their broad frequency spectrum clicks are not suitable for this purpose and so the use of tone bursts, tone pips (Davis and Hirsch 1976; Stillman et al. 1976; Kodera et al. 1977; Weber and Folsom 1977; Suzuki et al. 1977; David and Hirsch 1979; Hayes and Jerger 1982) or filtered clicks (Brama and Sohmer 1977; Klein and Teas 1978; Coats et al. 1979) have been strongly suggested. Tone pips or tone bursts are more likely to give maximal excitation at the same location on the basilar membrane than wide-band clicks in normal and pathological conditions. Clicks will tend to stimulate a more extensive length of the cochlear partition. Therefore, in sensory hearing impaired patients the time to reach responsive areas on the basilar membrane is built upon the location of the remaining sensory elements partitioned along the basilar membrane in response to the spectral sound content of the click. Since the spectral deficits among these patients can be highly variable, the stimulated parts of the basilar membrane when using broad band stimulation vary as well among these subjects and therefore result in different PLs of wave I and the succeeding waves. A drawback using frequency specific stimuli are their relatively slow onsets compared to clicks resulting in less synchronous neural activation, and consequently in less BAEP resolution. This manifests itself particularly at stimuli frequencies used below 2000 Hz for testing apical regions of the cochlea. Improving BAEP resolution in such cases has been achieved by appropriate high pass filtering, i.e., a cut off frequency set at 30 Hz (Suzuki and Horiuchi 1977). Generally, attempts in clinical

practice have been fairly succesful up to now using frequency specific stimuli exceeding 2000 Hz. One must first consider that even frequency specific stimuli, owing to their steep envelopes have spectral spread to adjacent frequencies and second, as mentioned previously, the response is not entirely a reflection of the stimulus used as it is elicited by the very onset of the stimulus. Overcoming these imperfections two approaches have been developed on the basis of masking noise, thereby ensuring frequency specific audiometric thresholds in addition to rapid onset. One method involves the presentation of tone pips (Picton et al. 1979) or clicks (Pratt and Bleich 1982) mixed with notch-filtered noise, i.e., white noise with a band of frequencies rejected. This notched noise masks the frequency splash of the spectral sound content on the basilar membrane and leaves the nominal frequency domain of either click or tone pip unmasked. This method gives a better prediction of frequency specificity than potentials evoked by filtered clicks or tone pips alone. A second method involves the high-pass masking technique first described in animals (Teas et al. 1962) and later applied in humans using electrocochleography (Elberling 1974; Eggermont 1976). This technique considers recording potentials in response to wide band clicks in the presence of high-pass noise with varying cut-off frequencies. Subtraction of the wave forms carried out point by point by a memory computer yields the wave form in response to the frequencies between the respective cut-off values. The narrow band responses can be considered as reflections of frequency specific activity from the cochlear partition depending on the steepness of the low frequency slope of the high pass noise and the interval between the cut-off values. Its application has been investigated in BAEP (Don and Eggermont 1976; Parker and Thornton 1978) and correlated to psychophysical audiometric frequency thresholds that fitted extremely well (Don et al. 1979). In our study we have also used a more frequency-specific stimulus, i.e., a 2000 Hz tone pip for reasons to be discussed (see chapter 3).

Conclusions

Averaging the electroencephalogram (EEG) subsequent to, and synchronized to, repetitive auditory stimuli passed through a headphone permits the recording of BAEPs. These multiphasic series of electric potentials have proved to be useful in various publications for detecting hearing disorders in an objective way, provided that stimulus and recording requirements are met. Using only a headphone when facing hearing disorders can be disadvantageous as different types of hearing loss might yield the same response abnormalities. The additional use of a bone vibrator in conjunction with a headphone might partly resolve this puzzle, as it discriminates between sensorineural and conductive hearing loss in any specific case. Reports dealing with the application of bone conducted stimuli are scarce and mostly casuistic in origin. Gauging its profits and limits have not been sufficiently subjected to research up to now. A systematic study employing both stimulators carried out in a more extensive group of patients before and after treatment as well as in a control group has not been described recently. This scheme tests its clinical significance as a diagnostic aid and attributes to the knowledge of bone and air conduction traveling paths.

CHAPTER 3

Comparison of the Latencies between Bone and Air Conduction in the Auditory Brainstem Evoked Potential

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Brainstem evoked potentials (BEPs) elicited by air conducted (AC) signals have been thoroughly investigated recently. Their application to establish neurological and audiological deficits in an objective manner has been widely accepted. BEPs to bone conducted (BC) signals have, however, received less attention, due to technical problems related to the bone vibrator itself (Jerger and Hayes 1976; Galambos and Hecox 1978; Picton and Smith 1978; Kavanagh and Beardsley 1979; Mauldin and Jerger 1979), i.e., the poor frequency response and limited energy output, the electrical induction at the electrodes and finally the need for appropriate masking of the untested ear, which we investigated (Boezeman et al.1983)(see chapter 4). Perception of BC signals is not affected by conductive loss and needs only to exceed the cochlear threshold to elicit a response. In clinical neurology this feature may surpass the value of the AC response when dealing with patients suffering from both neurological and conductive disorders. In clinical audiology BEPs to BC signals, in addition to AC signals, provide an estimation of the air-bone gap as a part of the hearing loss, situated in the middle ear, that can often be eliminated by treatment. The present study deals with the generation and the physical and psychophysical calibration of the selected stimulus, as it is important to have similar outputs from the two stimulators when comparing both responses at comparable sensation levels. Furthermore, this paper discusses the latency difference of wave V observed between the two responses.

Experimental procedure

Stimulus: generation, transduction and frequency analysis

We used a standard audiometric bone vibrator (Radioear B71) and electromagnetically shielded earphones (TDH 39) fitting in a headset with supra-aural cushions. The stimulus to evoke potentials was a 2000 Hz computer-generated tone pip, shaped by a low pass filter (Krohn Hite 3344) set at 9000 Hz. Its envelope was trapezoid with rise and decay times of 1 msec each (2 cycles) and a duration of 2.5 msec (5 cycles).The electrical signal to the input of the bone vibrator and the acoustic signal generated were displayed on an oscilloscope employing an artificial mastoid (type 4930, B&K) connected to a precision sound level meter (type 1613, B&K). The AC signal was displayed in the same way as the BC signal using a 6 ml coupler (type 4152, artificial ear, B&K). Fig.2 (left) presents the transducted signals of both stimulators in comparison with the 2000 Hz electrical input signal and shows the acceptable similarity of the acoustic wave forms. Spectral analysis of these wave forms using a real time frequency analyser (type 2116, B&K) showed a clear specification around 2000 Hz without a distinctly adverse effect from other frequencies. Furthermore, for comparison spectral analysis was carried out of continuous tones with the same frequency presented to both stimulators (fig.2 right). The spectral contents of both tone pips were about 1/3 octave wide (-3dB) with 30 dB/octave roll off, averaged over high and low frequency skirts. We found that using stimuli of shorter duration and with steeper slopes the bone vibrator showed distorted wave forms compared to the input signals. For this experiment we used: one halversine of 3000 Hz as used by Mauldin and Jerger (1979), 5 cycles of 4000 Hz and a rectangular pulse of 0.16 msec (click). The results are shown in fig.3 (left) (page 52). Spectral analysis of these BC signals shows (fig.3 right) that the brief acoustic signal of 3000 Hz has a broad spectrum without any specification around 3000 Hz. The 4000 Hz signal possesses a frequency specification around 4000 Hz, but also augments lower frequencies around 500 Hz.

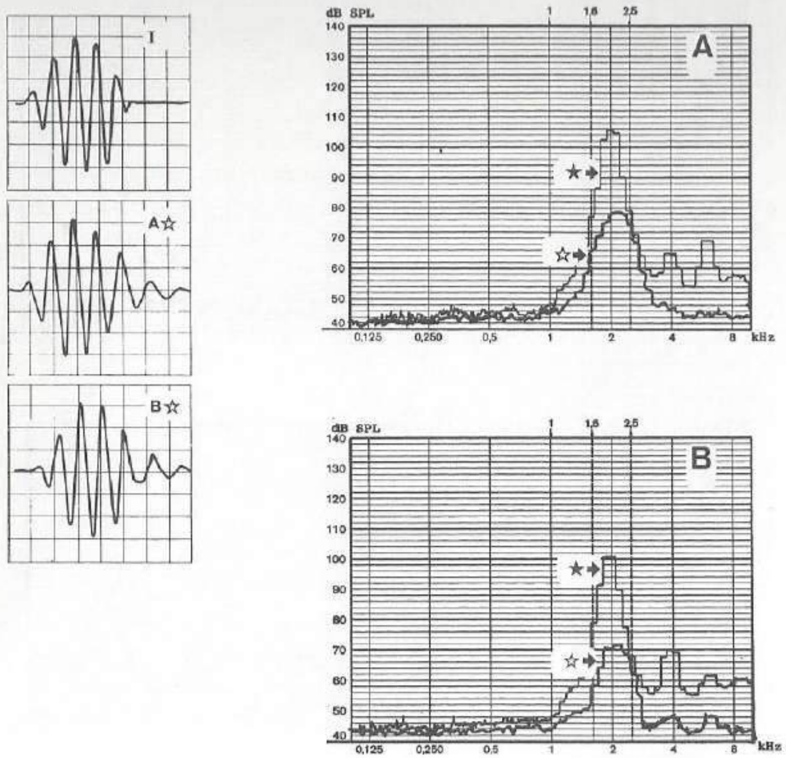

Fig.2. Left: graphic display of the 2000 Hz electrical signal (I) passed to the input of the earphone and bone vibrator, and the acoustic signals (A,B) respectively (time scale 0.5 msec/div.). Right: spectral analysis of the acoustic air (A) and bone (B) conducted signal. X-axis presenting the frequency indication and the Y-axis the intensity level, expressed in dB SPL. ★, pure tone analysis; ☆, tone pip analysis.

The results of the click yielded the same characteristics as it was with the 3000 Hz halversine and are therefore not shown. Summarizing the first part of this experimental procedure we decided to use the 2000 Hz tone pip for the activation of the bone vibrator and earphone.

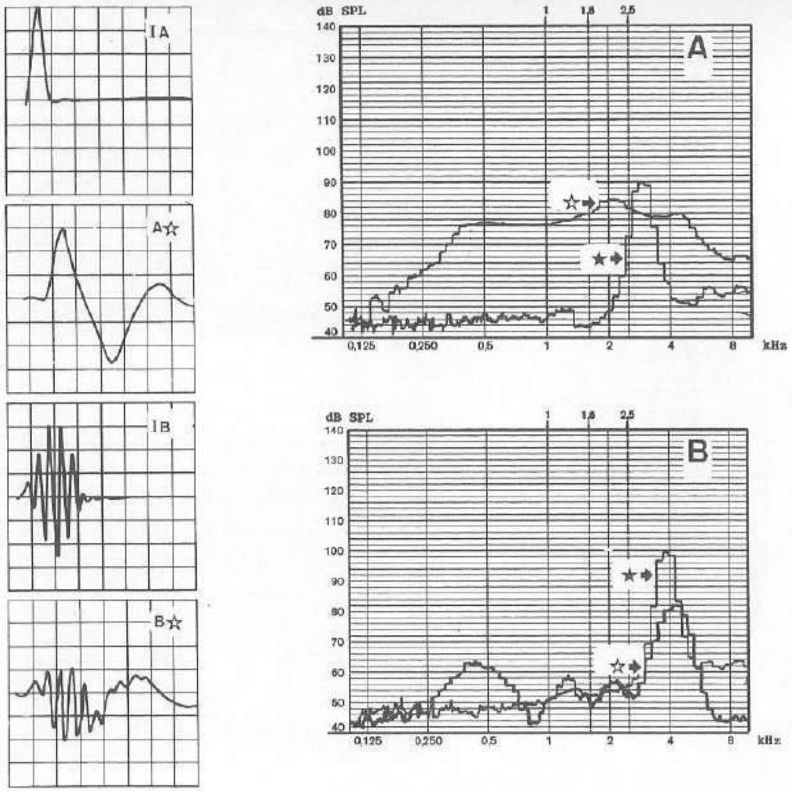

Fig.3. Left: graphic display of the 3000 Hz electrical signal (IA) passed to the input of the bone vibrator and the acoustic signal (A)(time scale 0.5 msec/div.) and of the 4000 Hz electrical signal (IB) to the input of the bone vibrator and the acoustic signal (B)(time scale 0.5 msec/div.) Right: spectral analysis of the BC signal (3000 Hz) in comparison with a continuous tone of the same frequency (A). The same procedure was performed for the 4000 Hz BC signal. X-axis presenting the frequency indication and the Y-axix the intensity level, expressed in dB SPL. ★, pure tone analysis; ☆, tone pip analysis.

The use of shorter time durations and steeper slopes should be preferable as it gives better BEP resolution. Nonetheless, this was avoided as it will very likely result in different acoustic spectra compared to those obtained from the earphone because of the limited amplitude-frequency characteristic of the bone vibrator.

Intensity

The calibration of the intensity of the stimulus (2000 Hz) was executed both physically and psychophysically. Considering the bone vibrator, as the sound pressure level (SPL) is not standardized internationally, we expressed the intensity of the AC and BC signal in dB HL peak. The amplitude of the third period of the stimulus, being the maximal level, was set to the same peak-to-peak amplitude of a continuous tone of 2000 Hz by means of an oscilloscope, using a Peters audiometer as an attenuator. The psychophysical calibration of both signals was effected by measuring the hearing thresholds in subjects with normal audiograms and without neurological disorders. The untested right ear was masked using one-half of the earphone to apply narrow band noise centred around 2000 Hz, 2/3 octave wide, 24 dB/ octave roll off at 70 dB SPL. The bone vibrator, placed on the forehead, was fed with the stimulus at 11/sec whereafter the subject was asked to indicate the level at which the signal was inaudible. The same procedure was applied to the air conduction system using the second half of the earphone which was placed over the left ear. For the AC signal this level was 22 dB HL peak (SD 5.5) and for the BC signal 29 dB HL peak (SD 4.0). For all subjects the BC level exceeded the AC level. We evaluated also the masked threshold procedure, i.e., estimating the detection threshold of the brief stimulus through a fixed noise intensity. The untested right ear was masked as above. The intensity of the narrow band noise (2000 Hz) presented to the left ear was kept constant at 60 dB HL and 40 dB HL respectively for calibrating the AC and BC signals. The subject was asked to indicate the level when the signal was just masked. Both signals were successively presented. For the AC signal this level was 83 dB HL peak (SD 0.71) and for the BC signal 70.1 dB HL peak (SD 3.51). Table 1 summarizes the signal-to-noise relation as found in both procedures. It demonstrates that this relation as found in the masked threshold procedure corresponds with the relation as found in the threshold procedure. No significant differences were found between the AC levels as did the BC levels ($P>0.1$, Wilcoxon's signed rank test). That means that for both signals the intensities used in the masked threshold procedure were not cross-heard by the untested ear and that the signal intensities used in the threshold procedure were not influenced by overmasking by way of noise presented to the untested ear.

Table 1.-Threshold Levels for Air and Bone Conduction Impulse Signals

condition	noise intensity (dB HL)	signal intensity (dB)	S-N (dB)
Air Conduction			
masking noise	60	83.1 ± 0.71	23.1 ± 0.71
no masking noise	0	22.0 ± 5.50	22.0 ± 5.50
Bone Conduction			
masking noise	40	70.1 ± 3.51	30.1 ± 3.51
no masking noise	0	29.0 ± 4.00	29.0 ± 4.00

Threshold levels in dB (mean±SD) of the impulse signals for air and bone conduction with and without masking noise, and the differences between the signal (S) intensity and the noise intensity (N) (mean SD) of both methods for each of the signals. No significant differences were found (P>0.1).

Considering this result, the masked threshold procedure seems to be preferable as its standard deviation is somewhat smaller compared to the one seen in the threshold procedure. According to these data bone conducted tone pips with the vibrator placed on the forehead had about 7 dB less sensation effect despite the two tone pips being equally attenuated physically. This is based on the fact that in clinical practice the bone vibrator is calibrated to be placed on the mastoid. From these psychophysical data the BC latency-intensity relation, as observed in the brainstem response, needs a correction of about 7 dB per subject to compare this relation at the same sensation level with the AC latency-intensity relation.

Polarity

Determination of the initial phase of the stimulus, i.e., rarefaction or condensation, was established in two steps. Firstly the acoustic signal as transduced by the earphone was displayed on an oscilloscope (Tektronix, TM 504, fig.4A). Then the output side of the earphone was covered with a sheet of stiff paper and a contact microphone (type Hellige) was held against it. By doing this, the contact microphone recorded the displacement of the pressure wave of the acoustic signal and demonstrates as shown in fig.4B that the first peak of this output is ascending.

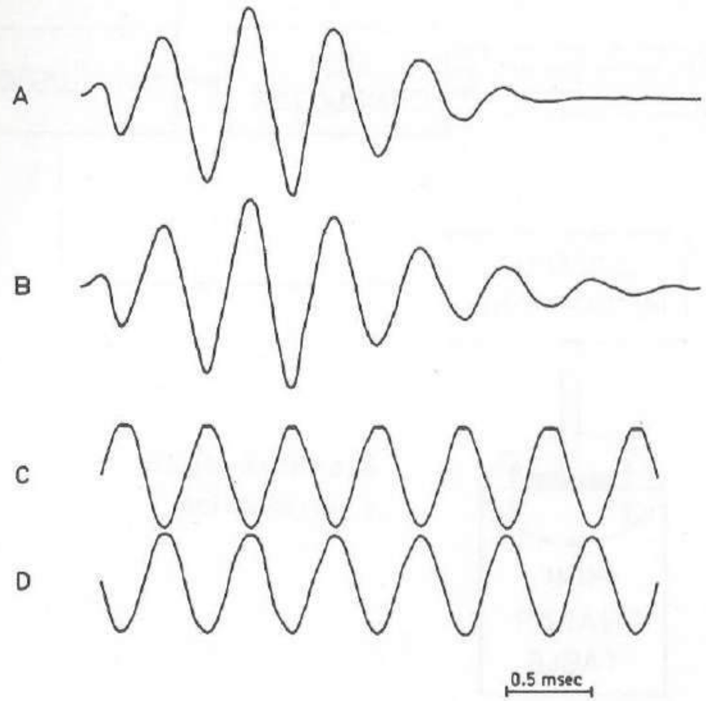

Fig.4. A, electrical input signal of 2000 Hz; B, acoustic signal from the earphone; C, continuous tone of 2000 Hz showing the clipping of the ascending sine waves; D, the output of the microphone during the presentation of the 2000 Hz continuous tone.

Secondly the microphones output had to be calibrated, as did its displacement. The microphone was therefore coupled to a minishaker table (type 4810, B&K) which was driven by a continuous tone (2000 Hz) generated by a Beat Frequency Oscillator (type 1022, B&K). The displacement of the microphone as driven by the minishaker table was further recorded by a lighted photo-sensitive semi-conductor (Silicon Photo Voltaic Cell). This semi-conductor was dimmed by an upward displacement of the microphone and imitated, by doing so, the effect of condensation (fig.5).

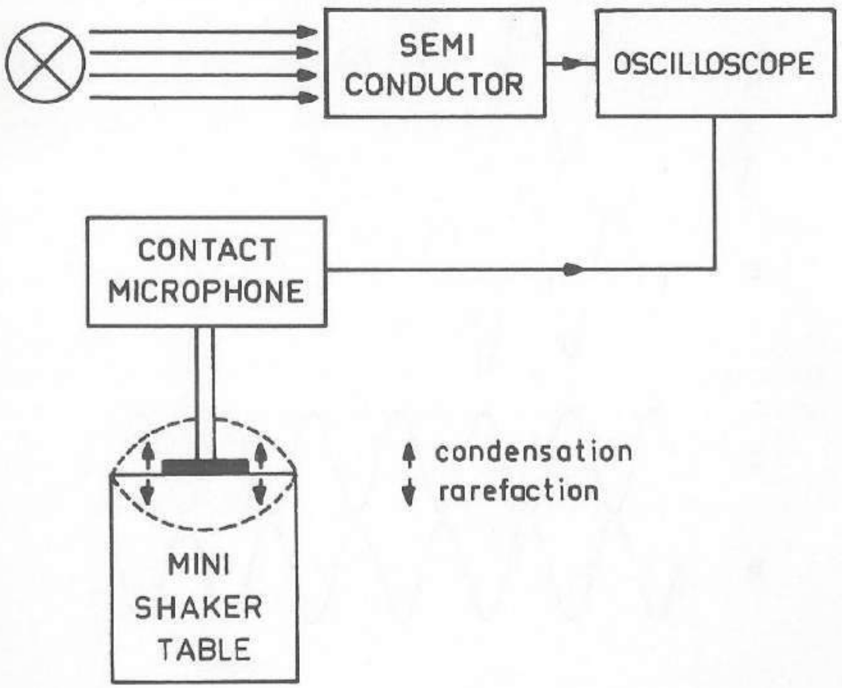

Fig.5. Calibration of the output of the contact microphone using a minishaker table and a lighted semi-conductor. The effects of condensation and rarefaction are displayed on the oscilloscope.

The display of that effect is shown in fig.4C, where the dimming of the lighted semi-conductor is represented by a clipping of the ascending sine waves. The output of the microphone during this displacement was recorded and is shown in fig.4D. This demonstrates that the output of the microphone when pointing downwards corresponds with an upward displacement. As mentioned previously the output of the acoustic signal was ascending and is the opposite of the output as recorded from the microphone during condensation. This means that the initial peak of the acoustic signal as transduced by the earphone corresponds with a rarefaction movement of the diaphragm of the earphone. This will result in an outward movement of the tympanic membrane and therefore to an upward displacement of the basilar membrane towards the scala vestibuli. For the bone vibrator the acoustic signal was displayed as mentioned previously. Next the input connector of the bone vibrator was adjusted so, that the phase of the acoustic signal was similar to that of the earphone.

Method

The subjects involved in the experimental procedure were tested once again. Evoked potentials were recorded to stimulation of the left ear by bone conduction (forehead placement of the vibrator) followed by air conduction. A commercially available holder and strap held the vibrator to the forehead with an application force of approximately 5N. The right ear was masked as in the experimental procedure by which overmasking was avoided. Both stimuli were presented at the following levels: 90,80,70, 60,50,40 and 30 dB HL peak. The bone vibrator was not used at 90 dB HL peak, as its output is limited to 80 dB HL peak.

Test-retest reliability

In 10 subjects the procedure was repeated after 6 weeks to establish the test-retest reliability of the measurement. The latency of wave V was measured per stimulation level in the test as well as in the retest session.

The reliability of the measurement was expressed by the standard deviation, computed by the formula:

$$S= \sqrt{\frac{\sum_{1}^{n} d^2}{2n}}$$

in which 'd' signifies the difference between the two measurements from one subject and 'n' indicates the total number of these paired measurements (=10).

Processing

A total of 2000 amplified (10^5) sweeps (repetition rate 11/sec) was averaged through an artifact detection/rejection window (DAV 62 averager, time window 20 msec, sampling rate 40 µsec, bandwidth -3 dB 90 Hz to -6 dB 3200 Hz). The time delay between the BC and AC signal was less than 0.1 msec and this has been ignored.

Recording

The cerebral activity was recorded bipolarly from the mastoid on the stimulated side to the vertex, with the occiput as ground, using standard EEG electrodes with electromagnetically shielded leads. Positive peaks (vertex positivity upwards) in the response wave forms were labeled by Jewett's convention (Jewett and Williston 1971). Each trial was performed twice and displayed on a scope. We measured the peak latencies (PLs) from stimulus onset to the positive peak of each wave and between two waves (interpeak latencies (IPLs), I-III, I-V and III-V) and calculated to the nearest 0.1 msec. Intertrial variability for PLs tended to increase with decreasing intensity, but remained within 0.05 msec. The IPLs were derived from the curves obtained at 70 dB HL peak and 80 dB HL peak stimulation for AC and BC respectively, having about the same sensation level. See block diagram in fig.6 showing the processing and recording equipment.

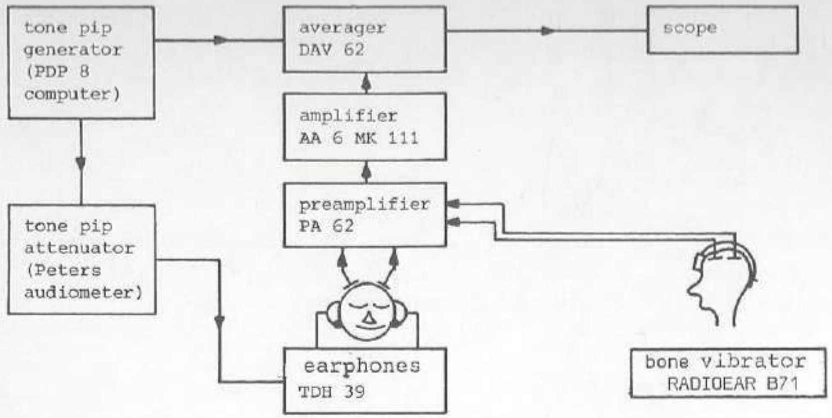

Fig.6. Block diagram showing the equipment for stimulus generation, processing and recording.

Results

Examples of both responses from one subject are presented in fig.7 (page 60). As shown the difference between the PL of wave V of the two responses amounts to 0.75 msec. The BC stimulus was 80 dB HL peak and the AC stimulus 73 dB HL peak, so having about the same sensation level. The BC and AC latency intensity relations of wave V from all subjects are presented in fig.8, taking into consideration that the BC stimulus had about 7 dB less sensation effect than the AC stimulus.

Test-retest reliability

Table 2 (page 61) shows the results of the test-retest reliability of this method expressed in the standard deviation in msec of peak latency V per stimulation level. This deviation varies from 0.08 to 0.15 msec (about 2 dB). Levels at 30 dB were not implicated because not all subjects showed a response near threshold. It appears that bone conduction has about the same reliability as air conduction. The standard deviation is also smaller at higher intensities in both responses, because the peak recognition is better.

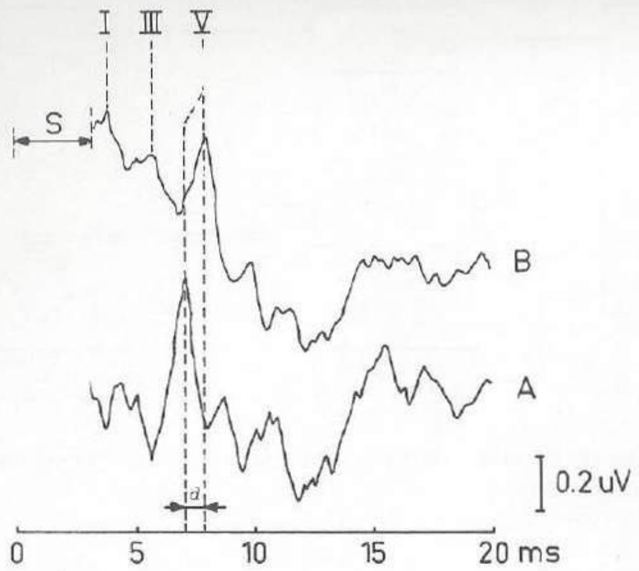

Fig.7. Example of the graphic display of an individual BEP evoked by air (A) and by bone (B) conduction. Stimulus intensity: (A) 73 dB HL peak and (B) 80 dB HL peak. S, stimulus artefact; d, difference in latency.

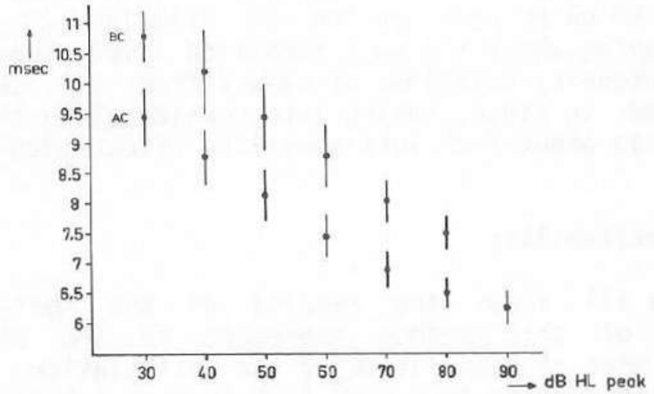

Fig.8. Air conduction (AC) and bone conduction (BC) latencies in msec of wave V as a function of intensity (dB HL peak). Mean latencies and SD are presented by black dots in the vertical bars respectively (N=22). The left ear was stimulated.

Table 2.-Accuracy of the Latency Measurement

stimulus intensity (dB HL peak)	air conduction (msec)	bone conduction (msec)
90	0.08	-
80	0.09	0.09
70	0.10	0.08
60	0.08	0.11
50	0.15	0.13
40	0.11	0.12

Accuracy of the latency measurement, expressed by the standard deviation in msec of peak latency V per stimulation level for AC and BC. The retest measurement was performed after a 6 weeks interval for each of the 10 subjects involved.

Statistical data analysis.

Curve fitting was applied per subject in order to investigate and therefore to compare latency-intensity relations for AC and BC stimulation at the same sensation level. We have fitted the latency-intensity data according to a power function as well as linear regression. Generally speaking a somewhat better fit can be obtained using power function as put forward by Picton et al. (1981). This was encountered by us with the AC latency-intensity relation from 30 dB to 90 dB and is most likely due to the fact that the AC curve starts bending very clearly to the level of saturation between the interval from 70 dB to 90 dB as shown in fig.8. The results of the fitting procedure for the BC latency-intensity relation from 30 dB to 80 dB showed no clear differences between either power function or linear regression. Since we wanted to investigate comparable latency-intensity relations at the same sensation level of both stimulators and since the output capability of the bone vibrator did not exceed 80 dB, we have applied linear regression analysis (Documenta Geigy 1968) using it as an approximation for the relations observed. For choosing comparable linear latency-intensity relations we investigated, for reasons stated above, whether or not it was justified to implicate the AC latencies for 70 dB in the linear analysis. This was carried out by comparing the measured latencies at 70 dB with those calculated for 70 dB according to the regression line fitted over the latency-intensity relation from 40 dB to 60 dB. Applying Wilcoxon's signed rank test (at a significance level of 0.01) the measured latency values deviated not significantly from those calculated, so we investigated the linear AC and BC latency-intensity relation per subject from 40 dB to 70 dB. The level at 30 dB was not implicated in the analysis because most subjects showed no reliable BC response near threshold. The regression coefficient (μsec/dB) per subject was calculated using the measured latency-intensity relations for 4 intensities (40,50,60 and 70 dB) for AC and BC. Wilcoxon's signed rank test showed no significant differences between both regression coefficients, so these parts of the regression lines may be regarded as being parallel. The next step concerned the comparison per subject of the latency for the AC and BC signal having the same sensation level. Because of the sensation difference of 7 dB, as discussed before, a latency of an intensity of 51.5 dB being near the middle of the linear regression interval (55 dB) for the AC signal had to be related to the latency of the BC signal of 58.5 dB. In formula:

$$dn = [aAn - bAn.(-3.5)] - [aBn - bBn.(3.5)]$$

- dn = latency difference between AC and BC signal having the same sensation level
- n = rank number subject
- aAn = AC latency of 55 dB level for that subject
- bAn = regression coefficient of the AC regression line of that subject
- aBn = BC latency of 55 dB level for that subject
- bBn = regression coefficient of the BC regression line of that subject

In this way the differences observed between BC and AC latency values showed that the corrected BC latencies for each of the subjects were still more delayed than those which were obtained by AC. The mean value of this difference

was 0.88 msec (SD 0.43). For the interpeak latencies as presented in Table 3 (mean±SD) the difference between the BC and AC response as found per subject was calculated. No significant differences were found between the two conditions applying Wilcoxon's signed rank test (P>0.1). The IPLs show values normally reported in literature (table 3).

Table 3.-Interpeak Latencies of Air and Bone Conduction Responses

IPL	air conduction (msec)	bone conduction (msec)
I-III	1.99 ± 0.11	2.01 ± 0.14
I-V	3.86 ± 0.12	3.99 ± 0.10
III-V	1.86 ± 0.09	1.99 ± 0.13

Interpeak latencies (IPLs)in msec (mean±SD) for AC and BC obtained from the curves at 70 dB and 80 dB respectively, with left ear stimulation. No significant differences were found (Wilcoxon's signed rank test, P>0.1) between the IPLs of the potentials evoked by AC and BC.

Discussion

A pulse of 2000 Hz having rise and fall slopes of 2 cycles proved to be a comparable stimulus presented to the inner ear by AC and BC stimulation. Because of the length of the stimulus needed for correct BC stimulation, the earliest waves (I and II) were sometimes poorly discernible in both responses, especially in those effectuated at high intensity levels (fig.7). Wave I setts off hardly without any delay following the stimulus artefact in both responses, which is disadvantageous for its recognition. Increasing the intensity of the stimulus for better resolution of wave I implies the vanishing of it in the artefact. Resolution of wave I in those cases was then obtained by decreasing the intensity of the stimulus. That supplied more delay but yielded less resolution, so additional averaging (4000 x) was needed. On one hand using stimuli for BC stimulation with shorter duration may be advantageous in this respect, but on the other hand may be self defeating, as comparison with the AC response becomes critical as mentioned previously. We experienced that clearing the artefact by alternating the polarity of the stimulus gives no better resolution, especially seen in the BC response.

As shown we have found a time lag between both responses of which possible causes are discussed in the following.

A possible cause to start with may be found in the occlusion effect, i.e., an increase in sensitivity for BC signals in the case of partial or complete closure of the external auditory meatus. The occluding device during our threshold measurements of the left ear with BC stimulation was the one-half of the earphone with a supra-aural cushion. If occlusion was involved the correction with 7 dB was not justified and should be replaced by the value found under the unoccluded condition. Dirks and Swindeman (1967) pointed out in their solid study dealing with occluded and unoccluded bone conduction thresholds that for 2000 Hz and up, using earphones with supra-aural cushions, the effect was negligible. That observation makes any involvement of the occlusion effect with our findings very unlikely.

Another possible cause is related to the central conduction time of both responses. As we have found no significant differences between the IPLs of both responses, a different conduction time existing in the brainstem for each of the signals can be excluded most likely as a contributing mechanism.

Yoshie (1973) and Berlin et al. (1978) investigated the air bone gap using BC electrocochleography. Yoshie (1973) found a discrepancy between the BC and the AC latency-intensity relation and supposed that spectral differences between the acoustic signals were responsible. This was also suggested by Mauldin and Jerger (1979) who found a difference between the two responses of about 0.46 msec for the PL of wave V from 4 subjects with normal hearing. They corrected the spectral differences by introducing a low pass filter into the air conduction system set at different cut-off positions. Nevertheless, the use of a low pass filter causes

a phase lag and thus a time delay. This effect becomes more pronounced when filtering takes place near the central frequency of the stimulus. When we used the same stimulus (3000 Hz halversine) and filter as these authors did, we observed a phase lag of 0.325 msec when shifting the cut-off frequency from 20000 to 2000 Hz. This is in agreement with the specification of that filter. When the trigger time of the averager was kept unchanged the correction in latency as reported in their study can be explained for a great part by this effect.

Another topic concerns the distortion of BC stimuli resulting from non-linear mechanical properties of the skull, as shown in human cadavers by Arlinger and Kylén (1977) and Arlinger et al. (1978). However, they found distortion of BC signals using 500 Hz tone bursts and no distortion at the higher frequencies which we used.

A different subject directly involved with BC stimulation implies the stimulation of skin tissues, which may possibly evoke somato-sensory potentials simultaneously. This stimulation mode may thus interact with the auditory stimulation. A report recently dealing with that subject comes from Drechsler (1980) by which the third branch of the trigeminal nerve was stimulated by electrical square pulses of 100 µsec duration. They found within a time epoch of 10 msec a systematic negative deflection at 5 msec followed by a positive deflection at 9 msec. The amplitude of that wave form configuration exceeded mostly 1 µV. Increase of the stimulus intensity, even painful ones, produced no systematic shift of that wave form complex involved. We found no such prominent waves in our BC response within 10 msec. Furthermore, a change of the loudness sensation of our stimulus was closely bound up with a corresponding shift of wave V (fig.8). Therefore our findings strongly suggest an auditory stimulation. The similarity of the IPLs as found for the BC and AC response attributes in this respect.

A point of interest concerns the difference in traveling time between the BC and the AC signals to reach the inner ear, stressed even more by the observation that in our foregoing pilot study the bone vibrator on the occiput gave shorter latencies (about 0.3 msec) then when placed on the forehead at the same sensation level. Aiming at a direct measurement of this time delay failed when recording potentials evoked by the vibrator placed on the mastoid because of the considerable electrical induction at the mastoid electrode, resulting from the electromagnetic radiation of the vibrator itself. Traveling time of BC signals was investigated by Wigand (1962), who found interaural time differences (0.3-0.9 msec) by measuring the upper limit temporal fusion of the BC and AC clicks (0.1 msec) in subjects with normal hearing. Wigand concluded to a traveling velocity of the BC signals of about 500 m/sec.

For a more detailed investigation of the problems stated above we will use the psychophysical method of cancellation, where the level and the phase of an AC pure tone is adjusted to cancel the auditory sensation of a BC pure tone (Békésy 1932; Khanna et al. 1976; and for clinical application Kapteyn et al. 1980). In a preliminary investigation applying this cancellation method using two continuous pure tones of 4000 Hz, we have found a systematic shifting of the phase of the BC signal in relation to the unchanged AC signal by replacement of the bone conduction vibrator from the forehead to the pinna in steps of 1.5 cm (thickness bone vibrator). This phase shifting amounted to about 33°/cm and implies a decrease of the time delay of the bone conducted signal in relation to the unchanged AC traveling way to the cochlea. The total wave length (λ) of the applied signal amounts to approximately 10.9 cm ($360^\circ/33^\circ$). Considering the signal's frequency of 4000 Hz the traveling velocity through the skull indicates roughly to 436 m/sec ($v=f.\lambda$). This is in reasonably good agreement with the results of Wigand (1962) as mentioned above. The difference in distance between the forehead and pinna being about 15 cm could coincide with a time delay of the BC signal of about 0.34 msec (15/43.2 msec) which is considerably less than the differences as found by Mauldin and Jerger (1979) and by us using BEP. We have devoted a prolonged study to the interdependent time relation of BC and AC signals as will be dealt with in chapter 5 en 7.

CHAPTER 4

Effect of Contralateral and Ipsilateral Masking of Acoustic Stimulation on the Latencies of Auditory Evoked Potentials from Cochlea and Brainstem

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When recording brainstem evoked potentials (BEPs), it can be necessary to mask the untested ear, i.e., contralateral masking of acoustic stimulation. We investigated the influence of masking because, when the untested ear is masked sufficiently, i.e., without overmasking, the perception of the tested ear may be influenced by the so-called central masking. Central masking (CM) manifests itself as a threshold elevation of one ear in the presence of a masking sound in the contralateral ear (psychophysical test), when a direct acoustic interaction between the two sounds is precluded (Zwislocki 1973). According to Zwislocki the greatest amount of central masking occurs when the masker and signal are close together in frequency and low-to-moderate masking intensities are used. CM is probably related to activity in the lower auditory pathways in animals, as shown by Goldberg and Brown (1969). This could also be true for humans (Zwislocki 1971, 1973), where bilateral representation is available at the level of the medial superior olive (Luxon 1981). As the auditory potentials are generated in the lower central auditory pathways in humans (Sohmer and Feinmesser 1967; Jewett and Williston 1971; Picton et al. 1974; Starr and Hamilton 1976) and in animals as well (Jewett 1970; Lev and Sohmer 1972; Buchwald and Huang 1975), we investigated CM effects at this level resulting from neuronal interaction and the possible frequency dependency of this effect when using different masking frequencies. To investigate the influence of overmasking, we used the method of ipsilateral masking of acoustic stimulation to mimic the situation in the case of overmasking and therefore the tone pip and the masker were presented to the same ear.

Material and Method

Stimulus

The stimulus to evoke the potentials was a 4000 Hz computer-generated tone pip shaped by a low pass filter set at 9000 Hz. Its envelope was trapezoid with rise and decay times of 0.5 msec each (2 cycles) and a total duration of 1.25 msec (5 cycles). The first peak of the acoustic signal produced a rarefaction movement of the tympanic membrane. The repetition rate was 11/sec. For the spectral analysis the same equipment was used as in chapter 3. Fig.9 presents the acoustic signal transduced by the earphone in comparison to the electrical input signal which demonstrates a close correspondence. The spectral analysis (fig.10) of this brief air conducted acoustic signal was carried out in comparison with the analysis of a pure continuous tone of the same frequency being transduced by the same earphone. The analysis of this pure tone was performed as a reference for the calibration of the tone pip. This analysis shows a clear specification around 4000 Hz without a distinctly contamination from other frequencies. The band width was about 1/3 octave (-3dB).

Noise

Narrow band masking noise was generated by an audiometer (Peters AP 6). Band width and spectral shape of this noise varied with the central frequency. For this analysis, the same equipment was used as in chapter 3. The smallest band width, being 1/3 octave (-3 dB), were found for high frequencies (4000 and 6000 Hz). The roll off values increased with increasing frequencies from 24 dB/oct at 500 Hz to 42 dB/oct at 4000 Hz and decreased to 30 dB/oct at 6000 Hz.

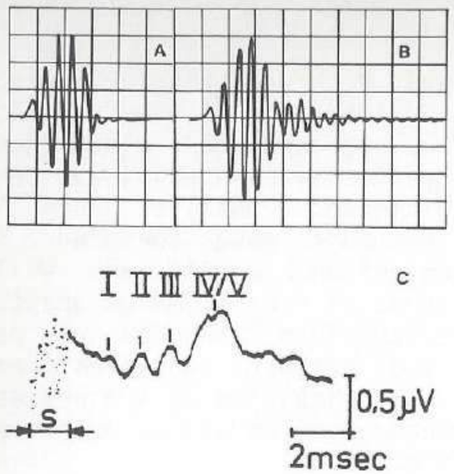

Fig.9. Graphic display of the 4000 Hz electrical signal (A) to the input of the earphone and the acoustic signal (B)(time scale 0.5 msec/div.). An example of the response is shown in (C). The successive waves are labeled with Roman numerals according to Jewett's convention. S, stimulus artefact.

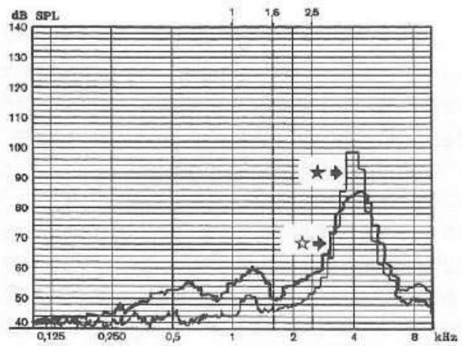

Fig.10. Spectral analysis of the tone pip and the pure continuous tone of 4000 Hz. X-axis showing the frequency indication and the Y-axis the intensity level, expressed in dB SPL. ★, pure tone analysis; ☆, tone pip analysis.

Recording

The cerebral activity was recorded bipolarly from the mastoid on the stimulated side to the vertex with the occiput as ground, using standard EEG electrodes with electromagnetically shielded leads. Each trial was performed twice and displayed on a scope. Positive peaks (vertex positivity upwards) in response wave forms were labeled according to Jewett's convention (Jewett and Williston, 1971). We measured the latencies from stimulus onset to the positive peak of each wave (absolute latencies of peak I, peak III and peak V) and between two waves (interpeak latencies I-III, III-V, I-V), calculated to the nearest 0.10 msec (maximal read-out inaccuracy 0.05 msec). An example of the response is shown in fig. 9C.

Processing

A total of 2000 amplified (x10.000) sweeps were averaged through an artifact detection/rejection window (DAV 62 averager, time window 10 msec, sampling rate 20 μsec, band width -3 dB 90 Hz to -6 dB 3200 Hz).

Contralateral masking

The stimulus was in all conditions presented to the left ear and the masker to the right ear. The peak latencies (PLs) and the interpeak latencies (IPLs) were measured during noise presentation increasing in steps of 10 dB from 50 dB SPL up to 90 dB SPL. Various central frequencies in a random order were used: 500, 1000, 2000, 4000 and 6000 Hz. Stimulus intensity was kept constant at 80 dB SPL peak, using the audiometer. For an accurately guarding of the stimulus intensity, its sound pressure level was measured with a precision integrating sound level meter (type 2218, B&K) with a peak hold setting facility for calibration of brief signals. For assessing the sound pressure level of the maskers the sound level meter type 1613 was used.

Ipsilateral masking

Stimulus and masker (noise with a centre frequency of 4000 Hz) were simultaneously presented to the left ear. The PLs and the IPLs were measured during noise presentation, increasing in steps of 10 dB from 30 dB SPL up to 70 dB SPL. For a central frequency of 4000 Hz the noise completely covers the spectral content of the stimulus and thus may be used as an adequate masker. Stimulus intensity was kept constant at 80 dB SPL peak.

Results

Wilcoxon's signed rank test was applied to test the results in both masking procedures. The individual data obtained per band width of noise and per masker intensity were compared to the data obtained without masking (paired observation, n=10). A $P < 0.05$ was considered as significant.

Contralateral masking

The absolute differences observed in these 300 responses concerning the PLs were very small, having either a negative or a positive sign for the subjects involved and ranging from minus 0.2 msec to plus 0.3 msec. For all masking levels with the various central frequencies we have not observed any significant effect ($P > 0.05$). However the noise centred at 4000 Hz with an intensity of 90 dB SPL, the effect concerning the PL of wave V approached the significant norm ($0.05 < P < 0.1$), i.e., the PLs for the subjects involved tended to be prolonged during masking. The data concerning the IPLs showed no significant effect ($P > 0.1$).

Ipsilateral masking

Table 4 (page 72) presents the effects of masking centred at 4000 Hz ipsilateral to acoustic stimulation and shows that the PLs were slightly prolonged at a masking level of 30 dB SPL, which has proved to be not significant ($P > 0.1$). Applying a masking level of 40 dB SPL the PLs observed were clearly significantly prolonged ($P < 0.01$) and increased even more at higher intensities, until no response could be recorded at a masking level of 70 dB SPL. The IPLs showed no significant alterations at increasing masking levels (P>0.1).

Table 4.-Effects of Masking Ipsilateral to Acoustic Stimulation

	intensity masker (dB SPL)				
	30	40	50	60	70
PL V	0.09 ± 0.12	0.32 ± 0.27	0.73 ± 0.64	0.91 ± 0.74	m
PL III	0.10 ± 0.13	0.24 ± 0.27	0.63 ± 0.66	m	
PL I	0.05 ± 0.92	0.15 ± 0.15	m		
IPL I-V	0.01 ± 0.03	0.05 ± 0.10			
IPL I-III	0.01 ± 0.03	0.00 ± 0.53			
IPL III-V	0.01 ± 0.03	0.05 ± 0.14	0.13 ± 0.15		

Differences in msec (mean±SD) between the PLs and between the IPLs obtained without masking and with masking ipsilateral to acoustic stimulation at 4000 Hz, at 5 intensities and a fixed stimulus intensity of 80 dB SPL peak. The symbol m signifies the masking level of that particular wave. PLs are significantly increased at masking levels exceeding 30 dB SPL (P<0.01) (N=10).

Generally, using a masking level of 90 dB SPL contralateral to acoustic stimulation is prone to develop cross-masking, i.e., an ipsilateral masking level of acoustic stimulation of 40 dB SPL or less dependent on the interaural attenuation of the headphone used. That means that the effect on the PL of wave V as observed during contralateral masking of acoustic stimulation using noise centred at 4000 Hz with a level of 90 dB SPL may be partly based on overmasking. This is supported by the observation involving the same subjects that the PLs attained during masking ipsilateral to acoustic stimulation centred at 4000 Hz with a level of 40 dB SPL were significantly more prolonged than PLs attained during masking contralateral to acoustic stimulation centred at 4000 Hz applied at 90 dB SPL (0.02<P<0.05).

Discussion

Two important points have to be considered when elucidating the data concerning masking contralateral to acoustic stimulation. Firstly, those small differences could be ascribed to our display inaccuracy of 0.05 msec and also to the individual latency variability across multiple runs within one test session. This intra-subject variability is small, as established by Thornton (1975) and could partly explain our results. Secondly, a factor that might have an influence is the so-called phenomenon of overmasking, which can be expected at masking levels exceeding 70 dB SPL when interaural attenuation of the headphone is 50 dB for the masking frequencies used (Lidén et al. 1958; Hood 1960; Naunton 1960; Palva and Palva 1962; Sanders and Rintelmann 1964). If central masking takes place in the lower brain stem, prolonged latencies and interpeak latencies would be expected. This is not in agreement to what we found, because our results could have either a positive (increase of latency) or a negative (decrease of latency) sign for the subjects involved. If these results represent neuronal interaction in the lower auditory brainstem the magnitude of that effect (about 1 dB) does not correspond with the amount of central masking, as Zwislocki et al. (1968) established psychophysically (2-4 dB). Chiappa et al. (1979) also found no significant latency alterations when using a square wave pulse for a stimulus and white noise for a masker. There was also no clear frequency specificity, as Zwislocki (1970) found when using different masking frequencies.

Considering BEPs, interaction in the lower auditory brain stem has been suggested. It involves the phenomenon of binaural interaction of which the reports dealing with that subject are quite controversially. The amount of binaural interaction can be measured by comparing the response to a binaural stimulus with the computed sum of the response to identical monaural stimuli presented separately. The interaction begins after wave III and has its maximum around wave V. Ainslie and Boston (1980) came to the conclusion that the recorded difference wave form was a result of cross-hearing at the monaural response because with the use of insert earphones the difference wave form is absent. Dobie and Norton (1980) and Hosford (1981) and Levine (1981) have determined binaural interaction in humans, of which the latter author established the effect of cross hearing in the difference wave form. Phraser et al. (1981) have demonstrated that the binaural interaction for the amplitudes of wave III and wave V is dependent on the interaural intensity differences at binaural stimulation. The main argue remains whether there is an extra generator especially concerned with binaural stimulation. Animal studies of the brain stem response to clicks suggest that there are definite binaural interaction effects in the lower auditory brain stem being mediated at the superior olivary complex and at the inferior colliculus, the origins of wave III and wave V respectively (Babighian et al. 1978; Huang and Buchwald 1978; Gardi and Berlin 1981).

Our findings have some practical consequences for masking when recording BEPs for neurological as well as audiological purposes. Generally, increasing air conducted masking to either ear will mask both ears by bone conduction. This basic masking dilemma arises because the cushions of the earphones begins to act as a bone vibrator when the earphone is activated at levels around 70 dB SPL in our case. Thus any air conducted masking delivered to one ear exceeding 70 dB SPL would be delivered by bone conduction to both cochlea at equal intensity. The masker intensity should therefore not exceed the interaural attenuation of the headphone used, because overmasking levels exceeding 30 dB SPL are prone to prolong the PLs considerably. Another problem arises if the air conduction threshold of the untested ear is elevated and sufficient masking of that ear involved is necessary. In that case high masking levels will certainly result in overmasking. In solving this problem one should consider the signal-to-noise ratio, i.e., the difference in dB levels between the stimulus and the masker intensity. As mentioned previously, a signal-to-noise ratio of 50 dB (80-30) in the masking condition ipsilateral to the acoustic stimulation gives minimal and non-significant alterations in the response. To minimize the effect of overmasking the signal-to-noise ratio must therefore be improved by

increasing the stimulus intensity. If a masking level contralateral to acoustic stimulation exceeds 70 dB SPL, the stimulus intensity should be increased by at least the same value to keep a constant favorable signal-to-noise ratio of more than 50 dB. This procedure for masking the untested ear should be carried out for each patient, and the intensities of the signal and the masker are therefore dependent on the threshold of the ear under investigation the threshold of the untested ear and the interaural attenuation of the headphone used.

An entirely different mechanism that might be responsible for the observed latency changes, the middle ear muscle (stapedius) reflex that responds bilaterally following an acoustic input of high intensity. The contralateral masking noise set at 90 dB SPL used in our study produced no such reflex, as measured with an impedance meter (Model ZO 73, Madsen Electronics), therefore excluding middle ear muscle activity as a contributing mechanism.

Considering that in clinical audiology it is often necessary to mask the untested ear and the alteration in the brain stem response is small, we assume that it is justified to mask the contralateral ear, ignoring the possible effect of central masking in the brain stem response. When masking the untested ear the intensity level of the masker should not exceed the intensity level of the signal using earphones having an interaural attenuation of at least 50 dB. This finding is especially important, for instance, in procedures for measuring BEP that present the signal to a bone conduction vibrator, because of the low threshold of shadow hearing by the contralateral ear in that case.

CHAPTER 5

Bone Conduction Measurement and Calibration using the Cancellation Method.

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The effective abilities of the cancellation method have been shown by Békésy (1932) to prove psychophysically that in the perception of bone conduction sound stimuli the inner ear is involved. By measuring the electric response of the cochlea for air and bone conducted stimuli Lowy (1942) proved, using the cancellation method, that the cochlea is stimulated in both situations in a similar way. An audible pure tone transmitted to a headphone to one ear can be cancelled by a tone led simultaneously to the same ear using the bone conduction vibrator. To achieve this cancellation the frequencies of both pure tones have to be exactly the same, and the amplitudes as well as the phase relation between the signals have to be adjusted very accurately. When a signal, in our case a sinusoid, is transmitted to one detector by two different transducers along different pathways, the detector is stimulated by a superposition of both versions.

In formula:

$$I(s)=A\sin\omega t+B\sin(\omega t+\Phi)$$

A presentation of the calculated stimulus is shown in fig.11 (page 78). When both sinusoids arrive at the detector in phase and with equal amplitude the result is a pure addition. When the signals arrive with equal amplitude but in opposite phase the result can be brought to an auditory null, i.e., both sinusoids cancel each other. The shape of the curve calculated is very steep. When the two signals have exactly the same stimulation intensity, a small phase shift around a phase angle of 180° implies a sharp decrease of the attenuation

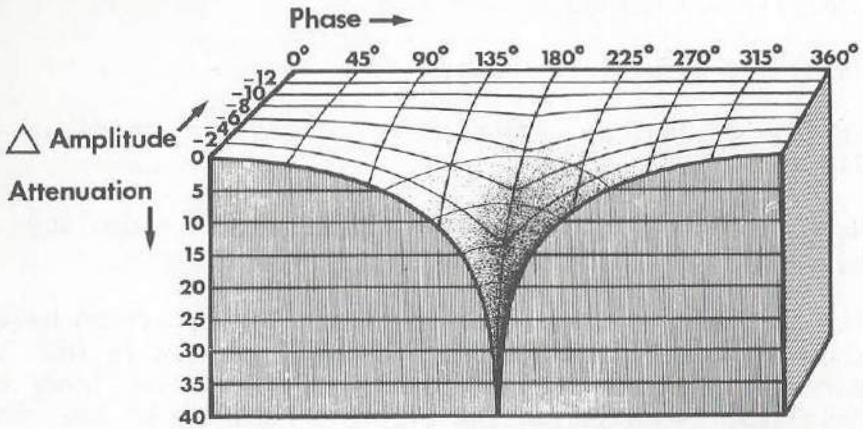

Fig.11. The Calculated Effect of Cancellation.

The cross section of fig.11 shows how a difference in amplitude of only 2 dB affects the course considerably, especially in the area around the phase angle of 180°. In that case the calculated maximum attenuation is seen to be about 20 dB instead of a complete cancellation. This attenuation will rapidly be reduced by increasing the difference between the amplitudes. Theoretically, cancellation is a very sensitive method for relating the intensity of two signals using the human ear, with its excellent dynamic range, as a zero detection instrument. We tested the utility of the cancellation method measuring the relation between the inner ear stimulation by headphone (TDH-39) and bone conduction vibrator (Radio Ear B71) placed on the forehead. The pure tone signal was generated by a generator (H.P.203A) having a second output of which amplitude and phase can be changed in relation to the first output. The two signals were connected to the input of a slightly modified two channel audiometer (Peters AP6). The test operator was able to change the intensity of both signals for reducing the influence of short term memory. During the adjustment procedure the contralateral ear was masked around the stimulus frequency by a narrow band noise

from a second audiometer (Peters AP5) presented to the second half of the earphone. In a previous study we found that contralateral noise up to 70 dB HL did not disturb the cancellation adjustment (Kapteyn et al, 1980). In a population of 27 young subjects with normal hearing a pure tone of 4.0 kHz at 60 dB HL activated a bone conduction vibrator. In clinical practice the bone conduction signal is calibrated for the vibrator to be placed on the mastoid, so in this experiment the sensation level is some dB lower as the vibrator was situated on the forehead. The subject had to adjust the phase and the intensity of the air conduction signal himself to achieve the cancellation. The results are shown in table 5.

Table 5.-The reliability of the Adjustment of Phase and Intensity

		CANCELLATION	N=27
	Bone	Air mean ± SD	Phase mean ± SD
test	60 dB HL	54.7 ± 2.8 dB HL	-39° ± 93°
retest	60 dB HL	54.5 ± 2.7 dB HL	-33° ± 100°
		intra-individual test-retest mean ± SD	
air-air=		-0.2 ± 2.0 dB	S= 1.45 dB
phase-phase=		-5.9 ± 19.1°	S= 14.2°

The mean values as well as the standard deviations are presented, while S (standard deviation) is related to the test-retest reliability of a measurement for independent paired observations from one subject. Headphone and bone vibrator were taken off and replaced between the tests. The accuracy of the amplitude adjustment is in agreement with the data calculated. The phase adjustment for the inter-individual results seems to be unpredictable and inaccurate. However, for the intra-individual test-retest results the accuracy proves to be high. In fact, relating the test results to fig.11 reveals that the phase accuracy, being 15°, is according to the accuracy in amplitude being 1.5 dB and concerns the tip of the funnel representing the attenuation of more than 20 dB. The inter-individual phase differences may be caused by the properties of the skull and scalp tissues. Tonndorf (1966) found a repeatability of the phase measurements within 2° but only when the vibrator had been cemented onto the mastoid bone. If skin was interposed the repeatability was not better than 15°. The amplitude was far less sensitive to the mode of coupling. Our results are also in agreement with data shown by Khanna et al. (1976). The continuation of this study is focused on the influence of these factors in the clinical applications of the cancellation method. Thus the cancellation method proves to be a very sensitive method for determining the stimulus intensity of the bone conduction signal. This fact opens perspectives in audiology for:

1) the calibration of the bone conduction vibrator

2) the fundamental problem of masking in the case of a maximum bilaterally conductive hearing loss.

ad 1) The calibration of a bone conduction signal has been a difficult subject up to now (Robinson et al., 1982). This is in contrast to the calibration of the headphone. Using the cancellation method a tone passed via a bone vibrator can be related very accurately to the calibrated headphone tone of the same frequency in a normally hearing subject. The only requirement is a two-channel audiometer having a second output of the tone generator and the ability to vary the phase angle between the signals from the two outputs. This can be achieved by an external box containing a phase shifter. This simple method by-passes the need for a reliable artificial mastoid. The correctness of the adjustment of the cancellation can be measured objectively by applying a combination of both cancellation and brain stem auditory evoked potentials. The cancellation is effected as descibed previously. Besides the continuous tone the headphone presents tone pips of the same frequency to the ear under investigation. Normally the pure tone will mask the tone pip but in the case of cancellation brainstem

potentials can be recorded. In this way the air-bone gap has been measured in a number of patients before and after middle-ear surgery both objectively and accurately (Boezeman et al,in press), as will further be dealt with in chapter 6.

ad 2) Considering a bilaterally conductive loss of about 50 dB it is open to doubt whether some of the thresholds observed are based on cross-hearing to only one bone-conduction threshold. The masking procedure normally used is not reliable in eliminating this doubt as the effective masking noise needed will also be overheard as the cross hearing level depends primarily on the physical quality of the headphone used.

Cancellation may solve that problem. When a continuous pure tone is presented at supra-threshold level by a vibrator situated on the forehead both inner ears will be stimulated at about the same intensity. When the same signal is simultaneously presented by the headphone to one inner ear, adjusted by the subject himself to the same sensation level, a change in the phase angle between the signals will influence the stimulus intensity in the ear being tested. In the case of cancellation the vibrator still stimulates the other ear, provided it has about the same sensitivity for that frequency, the subject will experience a lateralization of the sound source to the untested ear. However, if that ear is far less sensitive, the signal will disappear in the adjustment of cancellation. Thus the possible shift of the virtual sound source in the head demonstrates the equal sensitivity of both inner ears, as will be shown in chapter 6.

CHAPTER 6

Verification of the Air-Bone Gap in Patients with Mixed Hearing Disorders using the Cancellation Method and Auditory Evoked Responses to Air and Bone Conducted Stimuli.

Submitted for publication with T.S.Kapteyn, L.Feenstra and A.M.Snel

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The cancellation method is a very sensitive psychophysical test introduced by Békésy in 1932 by which the level and the phase of an air conducted (AC) pure tone is adjusted by the test subject to cancel the sensation of a bone conducted (BC) pure tone, the so-called cancellation point. This method has some major advantages compared to conventional audiometry for the estimation of the difference between AC and BC sensitivity (air-bone gap). Firstly, this method is very accurate in equalizing two stimuli using one inner ear as zero detector. This adjustment can be accomplished in subjects with normal hearing within 1-2 dB (Kapteyn et al. 1983 in press). Secondly, this adjustment is not affected by masking the untested ear. Applying masking noise will in fact facilitate this adjustment (Kapteyn et al. 1980). This procedure will give a clinical instrument detecting the difference between AC and BC sensitivity at supra threshold level in patients suffering from severe bilaterally conductive hearing loss, whereas the results obtained by measuring the audiometric thresholds are unreliable because of effects of shadow hearing and overmasking. Thirdly, relating the bone conducted signal to the air conducted signal affords an opportunity for calibrating the bone vibrator directly to the headphone, so bypassing the need for an artificial mastoid which is, as yet, not standardized internationally. A disadvantage of this method is the fact that the test operator can only provide instructions and guidelines to the subject, who has to adjust and to perceive the phenomenon of cancellation himself. The slightest movement of the head or jaw will usually upset the point of cancellation, so the subject must not talk or move briskly throughout a given test session. As the advantages outweigh the disadvantages we did choose this method, on which we have attempted to verify some aspects.

The first aspect of this paper deals with the verification of this cancellation point using AC brainstem responses in subjects suffering from hearing impairment.

Secondly, we determined the accuracy in measuring the air-bone gap using both the cancellation technique and the auditory brainstem response to AC and BC stimuli. The prediction capabilities of these methods were assessed to the behaviorally measured air-bone gap obtained by pure tone audiometry. Considering the cancellation procedure we used for comparison the difference as found between the AC and BC adjustment. In the AC brainstem response both the latency-intensity relation and the threshold of the response were used. The latencies of brainstem responses to BC stimuli were used in this way as a probe for detection of possible small perceptive losses, therefore increasing the accuracy of using evoked responses in the estimation of the air-bone gap.

Finally an attempt was made to show whether this test battery furnishes a reliable estimation of the improvement of middle ear function in patients undergoing middle ear surgery.

Material

Patients

In total 24 selected cases were investigated, all of whom were affected by unilateral conductive hearing disorders as well as by sensory hearing disorders to lesser extents. The ear contralateral to the most affected one showed only a small elevation of the AC conduction threshold if any. In those ears no sensory hearing impairment was noted audiometrically. Of these cases, 15 were female and 9 were male. Average age was 36.0 years, with a range from 19 to 66 years. Retrocochlear disorders were specifically excluded.

The patients had both ears examined. In each case middle ear surgery was conducted. 19 cases were operated upon for an otosclerotic conduction loss, 2 cases underwent a malleus-to-stapes ossicular reconstruction, and 3 cases a tympanoplasty type I Wullstein. Postoperatively recordings were taken from 18 stapedectomy cases and from 3 tympanoplasty cases. Thus data were obtained from 69 recordings.

Brainstem evoked potentials

Stimulus

A computer-generated 2000 Hz tone pip was passed into the headphone (TDH 39) and bone vibrator (Radioear B 71). Its electrical envelope was trapezoid with a rise and decay time of 1.0 msec each (2 cycles) and a total duration of 2.5 msec. The tone pip was shaped by a low pass filter set at 9000 Hz (Krohn Hite 3344). This envelope provided similar outputs from both stimulators as well as sufficient rapid onset to evoke potentials (Boezeman et al.1983). The spectral contents of the acoustic wave forms were about 1/3 octave wide with 30 dB/octave roll off. The stimulus was attenuated by an audiometer (Peters AP6).The intensity of the stimulus was expressed in dB HL peak (i.e., the plateau of the stimulus was matched to the peak-to-peak amplitude of a 2000 Hz pure tone using the audiometer).

Masker

Narrow band noise was applied, centred around 2000 Hz being 2/3 octave wide, 24 dB/octave roll off, generated by a second audiometer.

Processing

A total of 2000 amplified sweeps were averaged through an artifact detection/rejection window (DAV 62 averager, time window 20 msec, sampling rate 40 µsec, band width -3dB 90 Hz to -6dB 3200 Hz).

Recording

The cerebral activity was recorded bipolarily from the mastoid at the stimulated side to the vertex with the occiput as ground, using standard EEG electrodes with electromagnetically shielded leads. Each trial was performed twice and displayed on a scope. Positive peaks (vertex positivity upwards) in the response wave forms were labeled according to Jewett's convention (Jewett and Williston 1971). The latency from stimulus onset to the positive peak of wave V was measured for the assessment of hearing sensitivity and calculated to the nearest 0.1 msec (See righthand side of the block diagram (fig.12) outlining the BAEP equipment).

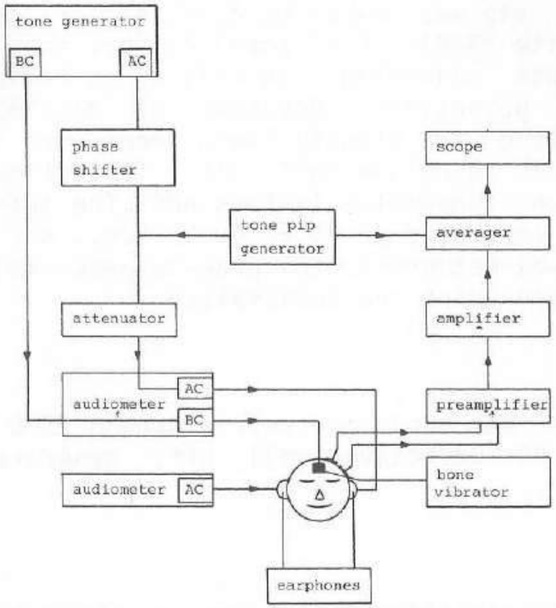

Fig.12. Block diagram showing the BEP equipment (right) and the cancellation equipment (left).

Cancellation

The ear and bone vibrator were fed by a tone generator (H.P.203A) having a second output (AC) of which the amplitude and phase can be varied in relation to the first output. For this purpose these 2 continuous signals were passed to the input of the slightly modified two channel audiometer. It was possible for the test operator to alter the intensities of the AC and BC signals. The subject could adjust the intensity of the AC signal in steps of 1 dB and the phase shifter in steps of 1 degree. (See lefthand side of the block diagram in fig.12 outlining the cancellation equipment).

Method

Audiogram

Audiograms were obtained from all subjects. The pure tone threshold of BC and AC at 2000 Hz was used. The estimation of the BC threshold (mastoid placement of the vibrator) from the less affected ear was difficult to assess in a few cases for sufficient masking of the poorer ear, having the largest elevated AC threshold,implies the possibility of overmasking. That means occasionally that the BC threshold of both ears could be estimated more accurately after successful operation on the poorer ear. We found no elevated BC thresholds ($\leqslant$ 15 dB HL) in the ears not operated on. In 3 cases a clearly defined Carhart notch (2000 Hz) was noticed in the ears submitted for operation. In 1 case this notch appeared in the affected ear after operation. Surgery in those 4 cases was conducted on the ossicular chain.

Brainstem evoked potentials

Evoked potentials were recorded from the tested ear by AC followed by BC stimulation (forehead). The untested ear was masked effectively in both modes. The AC stimuli were presented at the following levels; 100, 90, 80, 70, 60, 50, 40, 30 dB HL peak. The BC stimuli only at 80 dB HL peak, being the maximal undistorted output of the bone vibrator.

The BC stimuli were presented to both ears but the poorer ear, i.e., the ear submitted for operation was actually stimulated as the better ear was masked.

Cancellation

The tested ear was stimulated simultaneously at 2000 Hz by air and bone conduction. The intensity of the BC signal (forehead stimulation) was kept constant at 60 dB HL. The subject, by adjusting the intensity of the AC signal as well as the phase shifter, indicated the point of cancellation after which the BEP stimulus was presented simultaneously with the pure tone into the earphone placed over the tested ear. The subject was asked to maintain the adjustment of both pure tones during the averaging of the EEG in response to the tone pip. As an example fig.13 is added, showing the relative positions of the signals involved at the point of cancellation. The upper trace in fig.13 shows the summation of the tone pip with the continuous AC signal. The bottom trace shows the tone pip alone in the case of cancellation because the BC signal (middle trace) arrives at the cochlea in a phase, which is oppositely to that of the AC signal. The adjustment of the intensity varied between 1-2 dB, as described elsewhere (Kapteyn et al. 1983). Because of the forehead stimulation the actual BC stimulation in the cochlea was somewhat lower. The magnitude of that effect was estimated per subject by repeating the cancellation with the vibrator placed onto the mastoid process. The untested ear was masked.

Data analysis

Wilcoxon's signed rank test was used to test significant trends between paired observations. To assess the prediction capabilities of the methods investigated, regression analysis was carried out between the BEP data (latency/threshold) and the audiometric data and between the cancellation and the audiometric data. This provided scattergrams showing the coefficient of correlation (r), the standard error (SE) of estimate and the slope coefficient of the least squares linear regression equation. Furthermore,

correlational analysis was applied to establish the functional relation between these data, i.e., to what extent the two variables vary together. By doing so we do not express one as a function of the other and thus assume that both variables are effects of a common cause. For this we considered the perpendicular distances from the data points to the curve instead of either vertical or horizontal distances (Deming 1943). This approach supplied the correlation coefficient (r), the SD of the data points localized around the curve and the slope coefficient.

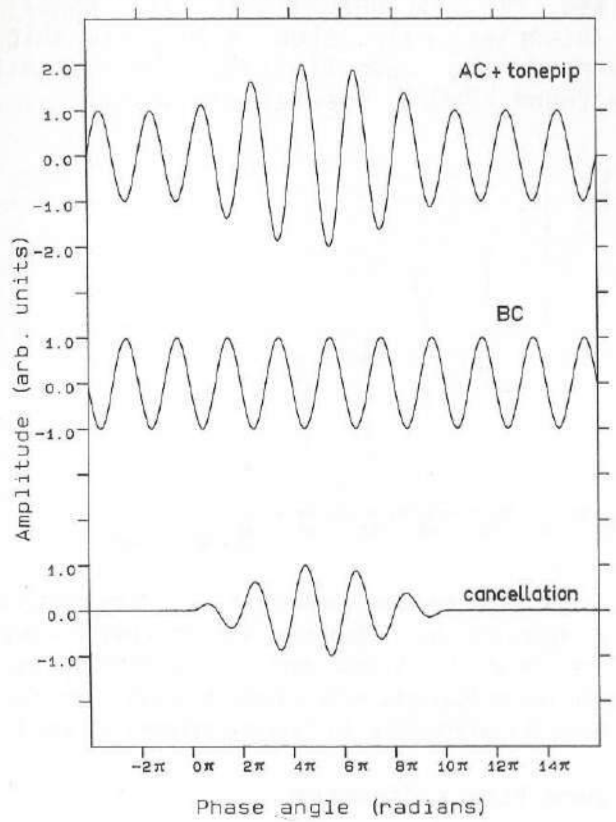

Fig.13. The upper trace shows both summated AC signals presented to the left ear. The bottom trace, showing the tone pip, corresponds with the point of cancellation because the BC signal (middle trace) cancels the auditory sensation of the AC signal and leaves the tone pip unmasked. X-axis shows the phase angle in radians between the 3 signals and the Y-axis the signal intensity in arbitrary units.

Results

Verification of the cancellation point

The (AC) latency value of wave V, obtained in response to the adjusted intensity during cancellation, was compared to the latency which would be obtained under the condition without cancellation. This latter value was calculated corresponding this adjusted intensity by interpolation using linear regression as described before in subjects with normal hearing (see fig.14)(Boezeman et al. 1983). Thus comparing the latencies calculated with those which were actually observed during cancellation. No significant differences were found (P>0.1, one-tailed, N=48).

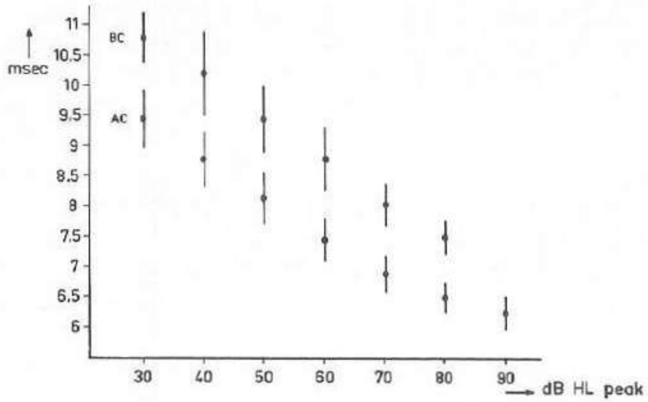

Fig.14. Air conduction (AC) and bone conduction (BC) latencies (in msec) of wave V as a function of intensity (dB HL peak). Mean latencies and SD are shown by black dots in the vertical bars respectively (N=22). In these subjects with normal hearing the left ear was stimulated. Note the difference in latency between AC and BC.

Cancellation vs pure tone audiometry

The difference between the intensities of the adjusted AC and BC stimulation (forehead) was calculated per subject. The air-bone gap was found by adding to this difference the effect of attenuation caused by forehead stimulation. Of

this the mean value was 6 dB (SD 2.5 dB). The individual cancellation and behavioral results giving the air-bone gap found at 2000 Hz are plotted in the scattergram in fig.15A (page 92). The error in prediction is derived visually from the scattering of data shown in fig.15A. This can be represented statistically by the standard error of estimate (SE). This is the measure of the SD of the distribution of the actual behavioral result around the value that is predicted by the regression equation.

Brainstem response latency vs pure tone audiometry

The AC latency-intensity relations found in the responses were shifted in different extents to the right in comparison to the AC latency-intensity relation found in the responses of subjects with normal hearing (fig.14). The hearing loss was estimated as follows: from the normal population regression equation of the AC latencies was calculated over the interval from 30 to 90 dB HL peak. This was also calculated for each case, involving the intensity levels applied. Next a fixed latency value of 7.0 msec was chosen, being about the middle of the latency interval, and the corresponding dB values, according to both equations, were calculated. The difference between these values corresponds with the predicted hearing loss given by the AC response. The air-bone gap was then estimated by subtracting any possible loss in dB as found by BC. For this a latency value exceeding 8.0 msec (>2SD) at 80 dB HL peak (fig.14) was considered as prolonged. Next, the BC hearing loss was estimated by calculating the corresponding dB value found in the normal population. For the non-operated ears the prolongation of the AC latencies was considered to represent the air-bone gap as the behavioral BC thresholds were not elevated. Fig.15B shows the scattering in the prediction of the air-bone gap.

Brainstem response threshold vs pure tone audiometry

The threshold of the brainstem response to AC tone pip signals was compared to the corresponding pure-tone threshold of that frequency.

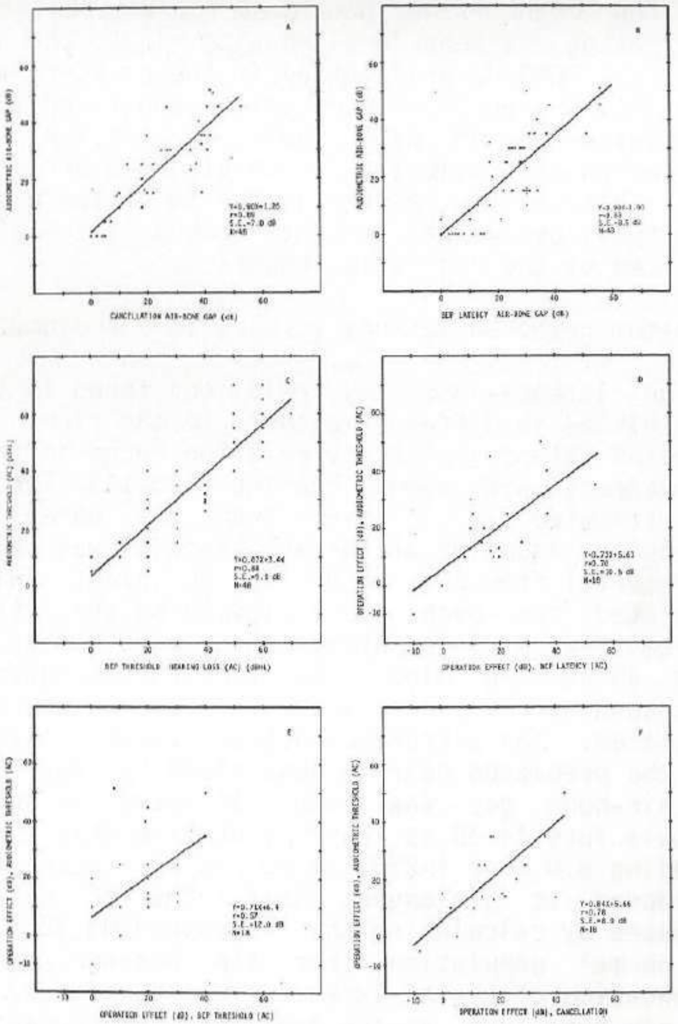

Fig.15. Scattergrams (A, B, C) show the preoperative results of cancellation and BEP. Scattergrams (D, E, F) show the effect of treatment. The equation, the correlation coefficient, the SE and the numbers of ears investigated are shown in the plots. All r values are significant for P .001, except for plot 3E for which P was .001-.01. Duplicate data points occupy a single space. All data are related to 2000 Hz.

The threshold of the response was defined as being the intensity level by which wave V was first discernible. The estimation of this threshold in dB was relative to the brainstem threshold of the AC response observed in the normal population of 22 subjects (fig.14). Fig.15C shows the results in the scattergram.

Middle ear surgery

The estimation of the effect of surgery on middle ear function is determined by the increase or decrease of the sensitivity of the air conduction system. All data obtained per subject before and after surgery were compared to the corresponding audiometric data (2000 Hz).

Effect upon air conduction

The AC sensitivity as shown by the behavioral thresholds was significantly increased after operation ($P<0.01, N=18$). The result of the operation was estimated behaviorally in dB by subtracting the AC threshold found after the operation from that found before. The (AC) latency-intensity relations found in ears after operation were shifted to different extents to the normal latency-intensity relation, depending on the improvement of middle ear function. The operation result was estimated in dB by comparing the latency-intensity relation obtained before operation with that obtained after, using linear regression analysis as used afore. The (AC) threshold elevation of the brainstem response found in ears before operation was compared to those found after. The difference in dB observed between these thresholds estimates the result of the operation. For the cancellation procedure the difference between the levels adjusted before and after operation shows the effect of treatment. Fig. 15D,-E,-F respectively, shows the prediction capabilities of these tests. An example of the recordings from 1 case is shown in fig.16A,-B (page 94).

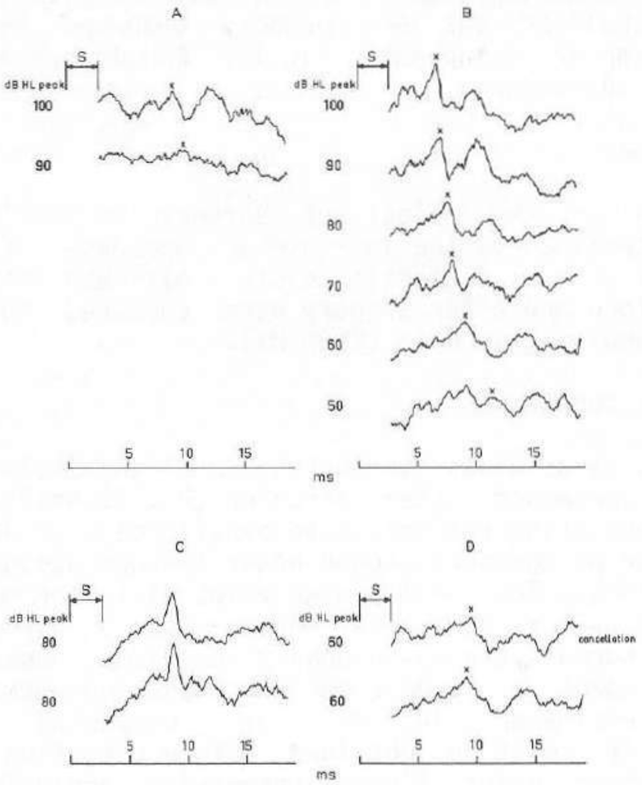

Fig.16. An example of evoked response recordings obtained from 1 case. A, shows the AC response taken preoperatively; B, shows the postoperative recordings. Note the decrease of the latency of wave V (x) and the decrease of the threshold for wave V after an successful operation on the ossicular chain. C, shows the BC response taken before operation (upper trace) and after (bottom trace). No significant change in latency is seen for the prominent wave V. D, shows postoperatively that the latency of wave V is not significantly changed under the condition of cancellation (upper trace) compared to the condition without it (bottom trace). S, stimulus artefact.

Effect upon bone conduction

The BC sensitivity was not significantly changed after operation shown by the behavioral thresholds and the latencies of the BC response (P>0.1, two-tailed, N=18). Furthermore we observed that the latencies obtained from the ears during the cancellation procedure carried out before and after operation showed no significant differences (P>0.1, two-tailed, N=18). See fig.16C,-D.

Effect upon phase relationship

The phase adjustments before operation were $162^{\circ}\pm107^{\circ}$ (mean±SD). After operation; $177^{\circ}\pm95^{\circ}$. The mean of the individual differences was $-15^{\circ}\pm152^{\circ}$. No significant trends (P>0.1) were found between the adjustments obtained before and after treatment.

Correlational analysis

In table 6 (page 96) the various correlational indices are indicated. All coefficients of correlation are significant. For the various measures the SD of the data points localized around the curve remains less than 10 dB. Mostly the slope of the regression equation is not closely around unity (=1) which will be discussed.

Discussion

The cancellation of 2 signals of identical frequency presented simultaneously to the inner ear via air and bone conduction channels proves to be reliable as shown by the BEP measurements. No significant prolonged latencies were measured. Normally the (AC) BEP stimulus will find the cochlea masked by the AC pure tone. The cancellation of this tone by a corresponding (BC) tone leaves the cochlear partition unmasked around the nominal frequency of 2000 Hz. This finding confirms objectively earlier cancellation experiments carried out in humans by Békésy (1932) and agrees with the conclusions reached later by Lowy (1942) using cochlear microphonics as response indicator.

We have tested the clinical applications of the cancellation method and evaluated its strength compared to BEP measurements. The error in the prediction (SE) of the air-bone gap using the cancellation method is less than that is found with BEP. The SE of 7.0 dB still implies a moderately high variation. This means that in the prediction of the air-bone gap an error of 14 dB (2SD) can be made.

Table 6.-Correlational Analysis of Corresponding Measures

		Coefficient of Correlation (r)	N	Significance Level P ( )	SD (dB)	Regression Equation dB/dB
All ears preoperatively						
behavioral air-bone gap	vs cancellation	.89	48	.001	5.0	1.00
behavioral air-bone gap	vs BEP latency (AC-BC)	.83	48	.001	6.1	1.10
cancellation	vs BEP latency (AC-BC)	.79	48	.001	6.9	1.10
BEP latency threshold (AC)	vs BEP threshold (AC)	.87	48	.001	6.6	.94
behavioral threshold (AC)	vs BEP threshold (AC)	.88	48	.001	6.4	.99
Ears submitted for operation						
behavioral threshold (AC)	vs BEP latency (AC)	.69	18	.001	7.1	1.18
behavioral threshold (AC)	vs BEP threshold (AC)	.75	18	.001	6.1	1.26
behavioral threshold (BC)	vs BEP latency (BC)	.50	18	.025	5.3	2.56
behavioral air-bone gap	vs BEP latency (AC)	.50	18	.025	8.1	.80
behavioral air-bone gap	vs BEP latency (AC-BC)	.64	18	.025	6.8	.90
Operated ears						
behavioral threshold (AC)	vs BEP latency (AC)	.70	18	.001	8.7	1.25
behavioral threshold (AC)	vs BEP threshold (AC)	.76	18	.001	7.2	1.40
Effect of operation						
behavioral threshold (AC)	vs BEP latency (AC)	.70	18	.001	7.9	1.04
behavioral threshold (AC)	vs BEP threshold (AC)	.57	18	.01	8.5	1.45
behavioral threshold (AC)	vs cancellation	.78	18	.001	5.7	1.09
Non-operated ears						
behavioral threshold (AC)	vs BEP latency (AC)	.79	24	.001	4.9	1.12
behavioral threshold (AC)	vs BEP threshold (AC)	.76	24	.001	6.0	.74
behavioral air-bone gap	vs BEP latency (AC)	.68	24	.001	5.7	.95

The three correlational indices are indicated in the table: the coefficient of correlation, the SD of the data points localized around the curve, the slope coefficient of the equation. BEP, brainstem evoked potentials; (AC), air conduction; (BC), bone conduction; (AC-BC), air-bone gap; N, numbers of ears investigated; P, significance level.

This applies even more for the BEP measurements (17-19 dB), of which this variation has also been shown in patients suffering from more neurosensory hearing disorders (Coats and Martin 1977: Jerger and Mauldin 1978; Hayes and Jerger 1982, Chisin et al. 1983). In tone burst electrocochleography this variation for conductive and neurosensory lesions at 2000 Hz was somewhat less (Eggermont 1976). Measuring the AC sensitivity to establish the effect of operation, the cancellation method predicts the audiometric data more accurately (fig.15F), compared to the BEP data (fig.15E,-F).

After operation the cancellation method shows a decrease of the air-bone gap, therefore indicating a positive result. In this respect the cancellation method may contain a pitfall. A seemingly positive result, i.e., a decrease of the air-bone gap, can be based on an elevated BC threshold. Thus a positive result of operation rests either upon an increase of AC sensitivity or a decrease of the air-bone gap, provided the latter is associated with an unchanged BC sensitivity. After operation the estimation of the BC sensitivity is important because middle ear surgery may influence the perception system disadvantageously. No such evidence was found in our 18 cases, shown by the audiometric (BC) thresholds and the evoked potentials elicited to BC stimuli. It was particularly noticeable in the combination of cancellation and BEP recorded simultaneously. The latter phenomenon shows that the measured latencies remain unaltered after operation. This indicates that the decrease of the level of the AC adjustment is accompanied by an increase of middle ear function. The same holds true for the converse situation. That means that in both situations the inner ear stimulation remains one and the same. But if prolonged latencies are recorded, this could point to an elevated BC threshold, provided that the procedure is properly carried out. For instance: in 1 case we observed a Carhart notch after an unsuccessful operation (the AC sensitivity decreased about 10 dB) the BC sensitivity was slightly decreased (about 5-10 dB) indicated by the BC BEP latency and BC pure tone threshold, but particularly so by the AC BEP latency under the condition of cancellation. On the other hand shortened latencies and a decreased BC pure tone threshold were noted in 3 cases having a Carhart notch preoperatively, that disappeared postoperatively. The systematic change of the BC sensitivity observed in those cases was small and therefore very likely did not influence the group statistics applied to the BC data. These observations confirm the opinion that middle ear surgery may directly influence the middle ear contribution in hearing by bone conduction, by either decreasing or increasing the impedance of the ossicular chain (Tonndorf 1966).

Two additional important findings concern the use of the cancellation method. Firstly, the observation that the adjustment was not altered by presenting masking noise to the untested ear in a range of 0 to 100 dB SPL (Kapteyn et al.1980). This shows that the method is not sensitive for overmasking whereas audiometry really is. It implies when dealing with bilaterally conductive hearing loss, as was faced by us in some cases before operation, that the air-bone gap of the less affected ear could more easily be estimated. This was emphasized after operation on the poorer ear which could then be masked sufficiently, that the audiometrically measured air-bone gap of the less affected ear was nearer the value of the cancellation result obtained preoperatively.

Secondly, when the cancellation of the auditory sensation in the ear being tested has been accomplished, the interruption of masking noise presented to the untested ear then leads to a shift of the virtual sound source to that side. This proves the equal sensitivity of both inner ears. If this shift does not occur, it proves that the untested inner ear is less sensitive. This phenomenon supplies an ideal tool in solving the surgeon's dilemma when dealing with severe bilaterally conductive hearing loss as follows: one inner ear may have more cochlear reserve than the other, or in an extreme case one inner ear may be totally deaf. The audiometric data provide, in the latter cases, only the BC sensitivity of one inner ear, of which the side is unknown. The cancellation method then simply supplies the balance between the residual cochlear functions, therefore giving

insight into the surgical risks to be taken. For instance, fig.17 shows the audiometrical results from 1 additional case suffering from severe bilaterally conductive hearing loss. Intentionally the patient's right ear was submitted for operation. We could not exclude the possibility of shadow hearing as the AC thresholds of the right ear shifted away by increasing the noise intensity in the left ear. The so-called Hood plateau was not clearly present. After the cancellation was accomplished in the right ear, no expected shift of the sound source to the left side was found. Thus the left inner ear appeared to be far less sensitive than the right one which was not demonstrated audiometrically. For this reason the patient was discharged from the operation schedule because an unfavorable operation result would diminish the sensitivity for hearing substantially.

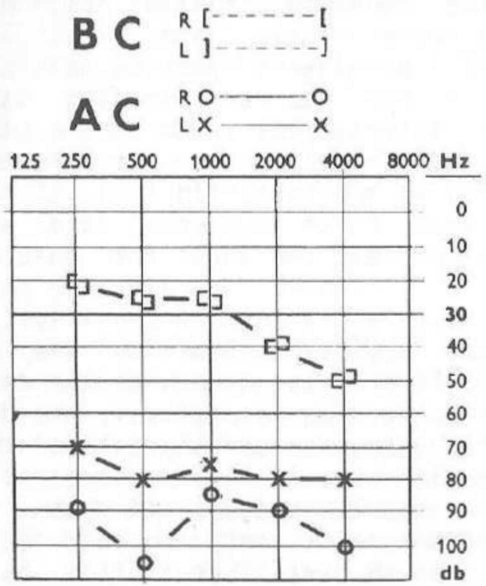

Fig.17. The tone audiogram of a patient suffering from severe bilaterally conductive hearing loss. The thresholds measured at the right ear might be caused by shadow hearing. BC, bone conduction; AC, air conduction.

Considering the correlational analysis (table 6) the cancellation method has a strong relationship with audiometric data, expressed by a high correlation coefficient and a small SD of the data points concerned. The slope of the regression equation is unity (=1) and that implies that only a constant correction factor (if needed) must be applied to find the corresponding audiometric data. For the following two BEP measures in table 6 the slopes of the regression equations are not unity, i.e., >1. Therefore these regression lines have a more steep slope, which intersect the horizontal axes on which the BEP data are expressed. This implies that BEP latency (AC-BC) indicates a small air-bone gap (<15dB) while both audiometric and cancellation data give none. Further, if there is an air-bone gap either found by audiometry or cancellation the BEP latency (AC-BC) will gradually under-estimate the corresponding data. The converse situation holds when the slope of regression is more flatly, i.e., < 1. It also implies that these BEP parameters must be multiplied by their slope coefficient to find the corresponding data. In table 6 the BEP measures latency (AC) vs threshold (AC) show a relationship close to unity as do also the measures behavioral threshold (AC) vs BEP threshold (AC). It appears from these findings that these measures have a close relation to unity, provided that the data are obtained by AC. It suggests that in finding the air-bone gap using evoked responses, the estimation of the BC sensitivity plays an important role and may possibly account for the effects seen. For further analysis of this assumption the data were splitted in two samples containing respectively the data of the ears submitted for operation and the data of the ears which were not. Both samples were in this respect related to the thresholds of the AC and BC system. In both samples (table 6) the correlation coefficients are less than those found in the main sample of 48 ears. That implies that the slope of regression coefficient might have a large deviation with which has to be reckon with. The measures BEP latency (BC) vs behavioral threshold (BC) point to a clear under-estimation of the behavioral threshold. A reexamination of the individual audiograms obtained preoperatively revealed that 3 cases showed a clear recruitment-like phenomenon of loudness in the ears

submitted for operation. This was based on the determination of the loudness discomfort level. Such a rapid increase of loudness sensation above threshold may very well affect the sensation of BEP stimuli because BEPs are approximately first discernible at 10-20 dB above the hearing thresholds of these stimuli. It is understandable that these phenomena appeared far less clear before operation considering the measures behavioral threshold (AC) vs BEP threshold (AC) (table 6) because the influence of recruitment was reduced by the conductive loss. After operation by which the conductive loss in these 3 cases was diminished, recruitment appeared more clearly as shown by the measures behavioral threshold (AC) vs BEP threshold (AC). It also affected the estimation of the effect of operation by BEP threshold (AC). Deleting from the samples the data associated with these cases showed slope equations which were far near to unity. Recruitment is not seen in audiometry as far as it concerns the estimation of the hearing thresholds. The cancellation by-passes this effect also, considering its close relationship to unity with audiometric data even in those cases showing recruitment. This makes cancellation also suitable for mixed hearing disorders.

Further we evaluated the usefulness of BC stimulation in BEPs by comparing the measures behavioral air-bone gap vs BEP latency (AC-BC) with behavioral air-bone gap vs BEP latency (AC). Table 6 shows that using the measure BEP latency (AC) alone over-estimates the air-bone gap while this is less with the additional use of BEP latency (BC) as indicated by a better correlation and a smaller SD of the data points concerned. The sample containing the ears not submitted for operation shows a somewhat different picture. The correlation coefficients and SDs are better compared to the previous findings. Scrutinizing the audiograms associated with those ears, no sign of recruitment was found. The measure BEP threshold (AC) tends to over-estimate the corresponding behavioral threshold. This is a more common feature possibly related to the residual noise after averaging.

Summarizing this analysis, one should give attention to the effect of recruitment when estimating the hearing thresholds with BEPs in patients having mixed hearing disorders. Furthermore the use of a bone vibrator favors the estimation of the air-bone gap in patients having unilateral air-bone gaps. When dealing with severe bilaterally elevated AC thresholds the value of BC responses will be substantially diminished due to masking problems (Boezeman et al. 1983). In this respect the use of cancellation should be considered.

The effect seen in the phase relationships is puzzling. The interindividual variability is high, as has also been found in subjects with normal hearing (Kapteyn et al.1983). After operation on middle ear structures no systematic shift in the relationship was found. The question is, whether this should be expected or not. The ossicular chain is thought to be markedly involved in hearing by bone conduction at 2000 Hz through the inertia of the middle ear ossicles (Tonndorf 1966). This "ossicular inertia" is modified by the impedance of the ossicular chain which may possibly decrease or increase after operation. A disadvantage underlying the use of continuous tones for phase relationship measurements is generally that there may be an undetectable shift of +/-(kx360°). Thus an adjustment repeated after operation may give no valid indication whether the phase relation has been shortened or lengthened in time. Trying to find an exact time delay between two signals, the use of AC and BC impulse signals such as tone pips may be advantageous when their phase and intensity adjustments have been computer-assisted. We have devoted a prolonged study to that subject.

Cancellation by itself supplies no detection of the cochlear reserve of one inner ear and considers only the difference between AC and BC sensitivity. So locking this cancellation method with BEP recorded simultaneously via AC stimuli provides an estimate of the cochlear reserve, as any existing conductive loss is compensated by the adjustment of AC stimulation. An important additional advantage is the use of a headphone for the estimation of the cochlear reserve, which makes sufficient masking far less troublesome as it is with BC stimulation. The cancellation method is accurately

in situations in which pure tone audiometry fails, but because of the subjective adjustment, the use of BEP for an objective verification is advisable.

CHAPTER 7

Phase Relationship and Amplitude Ratio between Bone and Air Conduction Pathways using the Cancellation Method with Impulse Signals and Brainstem Auditory Evoked Potentials.

Submitted for publication with A.W.Bronkhorst, T.S.Kapteyn, A.Houffelaar and A.M.Snel

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This chapter is directed to the phase relationship between signals transmitted along bone and air conduction pathways. We examined this relationship with the cancellation method by which the sensation of a bone conduction (BC) signal is brought to an auditory null by a simultaneously transmitted air conduction signal (AC) by adjusting the amplitude and phase angle between those sinusoidal signals. (Békésy 1932). In an earlier study (Boezeman et al.1983) using brainstem potentials (BEP) evoked by a 2000 Hz tonepip we found that the AC response showed latencies which were shorter compared to those found in the BC response. It showed a phase lag, i.e., a corresponding time lag of about 0.88 msec. The stimuli used in that study were equalized to the same loudness making use of threshold measurements, by which the bone vibrator was placed on the forehead throughout the test sessions. The results strongly suggested a delay in the BC traveling path. Using the very accurate cancellation method for equalizing the loudness of 2 continuous tones, Tonndorf (1966) showed in cats that there was a tendency for the bone input to lead the air input. This effect was shown by the phase readings during the cancellation of the cochlear microphonic responses. These findings agreed with a relative delay in the AC traveling path when the vibrator was placed to the side of the skull near the pinna. A disadvantage existing in phase relationship measurements using continuous tones is generally that the phase readings may contain an undetectable shift of $\pm(k\times360^{\circ})$. This drawback may be surpassed with the cancellation method, which we used with impulse signals such as tone pips by which both the adjustment of intensity and trigger point have been computer-assisted. That will supply an exact valuation of the time relationship and amplitude ratio between both signals during cancellation. We also tested whether this time relation was affected by changing the polarity of the BC signal. That means that both tone pips were set off in phase either identically or oppositely. This was further investigated by simulating the interaction between both tone pips with a mathematical model to demonstrate that our psychophysical findings were understandable and could be considered as reliable. In addition we verified these subjective findings objectively using BEP elicited to similar signals. The results of the BEP findings presented herewith are discussed with those which we described earlier (Boezeman et al. 1983). Furthermore we extended the cancellation experiments to continuous signals to investigate their relation to the results found with impulse signals. Next, aiming at a direct measurement of the time delay through the skull for the BC tone pip, we changed the position of the bone vibrator on the head. In addition we changed the frequency of the signals. Preliminary results of both last-mentioned changes are discussed.

Material

Instrumentation

The equipment for signal generation and detection outlined on the lefthand side of the block diagram (fig.18), consisted of 2 wave form generators, a timer and an attenuator, which were specially designed for this purpose. For programming and control, this equipment was connected to a micro-processor system (Tex.Instr.,TMS 9900) via a bi-directional data and control bus. Each of the two generators had a memory device having 1024 addresses with a word length of 12 bits. Furthermore these generators had a built-in recirculating facility commanded by the timer to have control over the repetition rate. To effectuate a time delay (Δt) between the two signals the slave generator (S.G.) was started after the onset of the master generator (M.G.) corresponding to a number of addresses being selected beforehand.

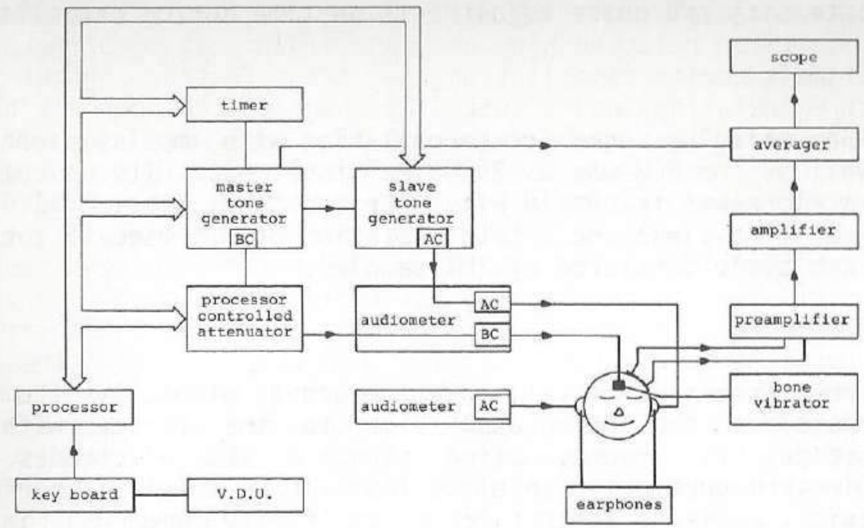

Fig.18. Block diagram showing the cancellation equipment (left) and the BEP equipment (right).

The master generator (M.G.) controlled Δt by which Δt was directly related to the number of addresses. As the memory of each of these generators had 1024 addresses to be filled, the step width of Δt depended on the frequency of the sine wave used as well as on its number of stored cycles. During the interstimulus time both generators were not active. The M.G. supplied the BC signal whereby its onset was accompanied with a trigger pulse (time width 0.1 msec) to start the averager used for processing evoked potentials. The S.G. dealt with the generation of the AC signal. The theoretical step width of the attenuator was 1/32=0.03 dB. Practically a step width of 0.1 dB could be achieved (± 0.05 dB). The range of adjustment was 100 dB of which the absolute accuracy was determined using a sound level meter (type 1613,B&K) either connected to a 6 cc coupler (type 4152, artificial ear,B&K) or to an artificial mastoid (type 4930,B&K). For further input/output of data a keyboard and a Visual Display Unit (VDU) were used to generate any desirable sine wave and for showing the results of the intensity and phase adjustments on time during cancellation.

Stimulus

The stimulus used for cancellation with impulse signals as well as for BEP was a 2000 Hz tone pip. Its electrical envelope was trapezoid with rise and decay times of 1.0 msec each (2 cycles) and a total duration of 2.5 msec (5 cycles). Each cycle consisted of 204 samples.

Recording

The cerebral activity was recorded bipolarly from the mastoid on the stimulated side to the vertex with the occiput as ground, using standard EEG electrodes with electromagnetically shielded leads. Each trial was performed twice. Positive peaks (vertex positivity upwards) in the response wave forms were labeled according to Jewett's convention (Jewett and Williston, 1971). For the assessment of hearing the prominent wave V was used, measured from stimulus onset to its positive peak, calculated to the nearest 0.10 msec.

Processing

A total of 2000 amplified sweeps were averaged through an artifact detection/rejection window (sampling rate 40 µsec, band width -3dB 90 Hz to -6 dB 3200 Hz, time window 20 msec). The BEP equipment is shown in fig.18 (righthand side).

Method

10 subjects with normal hearing participated in this study (5 females, 5 males).

Cancellation

The left ear was simultaneously stimulated by tone pips via both air and bone conduction channels using a TDH 39 earphone and a bone vibrator (B71) placed on the forehead

with an application force of 4-6 N. The intensity of the BC tone pip was preset at 60 dB HL peak. According to our previous findings (Kapteyn et al. 1983) the actual BC stimulation is somewhat lower (about 7 dB) due to the position of the vibrator on the forehead, so the intensity of the AC signal was fixed at 53 dB HL peak. The trigger point of the AC signal was preset to zero by the test operator, i.e., the time lag between the signals (Δt) was zero. The subject seated behind the keyboard was able to adjust the intensity of the BC signal as well as the trigger moment of the AC signal. A phase shift of at least 1.8° could be supplied giving a minimal stepwidth of 0.0025 msec for the AC tone pip to probe the BC tone pip lengthwise. For an appropriate loudness detection, the repetition rate was set at 75/sec. The subject was asked to indicate successively with the two given polarity combinations the clearest maximal and minimal loudness sensations occurring in the left ear. The untested ear was not masked, implying that a minimal loudness sensation occurring in the left ear was accompanied by a shift of the virtual sound source to the right ear. In this way the detection of minimal loudness sensations was facilitated. For the cancellation procedure with continuous tones a signal of 2000 Hz was used which was generated and applied similarly. The subject was asked to cancel the auditory sensation of both continuous tones.

BEP

After the cancellation procedure was finished, BEPs were elicited separately via BC and AC by 2000 Hz tone pips to the corresponding intensity adjustments. The averager was triggered by the onset of the BC signal. In the case of AC stimulation, the time lag adjusted between both signals was reset to zero by the test operator. The repetition rate was 11/sec. The untested ear was masked at 70 dB SPL.

Mathematical model

The two tone pips (Y respectively Y') used in our study were shaped linearly according to the formula (eq.1) as follows:

eq.1

$$Y,Y'\ (\omega t)\begin{cases} =0 & \omega t<0\ \vee\ 10\pi\leq\omega t \\ =\frac{\omega t}{4\pi}\sin\omega t & 0\leq\omega t<4\pi \\ =\sin\omega t & 4\pi<\omega t<6\pi \\ =\frac{10\pi-\omega t}{4\pi}\sin\omega t & 6\pi\leq\omega t<10\pi \end{cases}$$

eq.2

$$E(\pm)(\Phi)\rightarrow=\int\{Y(\omega t)\pm Y'A(\omega t-\Phi)\}^{2}\,\omega dt$$

In order to obtain an estimate of the loudness variations produced by partially overlapping tone pips, set off in phase either identically or oppositely, we calculated the energy content (E) of the sum of these tone pips as a function of phase angle difference Φ and amplitude mismatch A shown by eq.2 (see above), in which the integral covers both tone pips.

Results

The result of this mathematical approach is plotted in fig.19: A rising deflection signifies the maximal calculated intensity at a given time lag. A falling deflection reflects the opposite phenomenon. They are both plotted on a logarithmic scale (dB) relative to the energy content of non-overlapping tone pips (E=0) and both for an amplitude mismatch of respectively 0, -6, and -12 dB. Any mismatch between both intensities affects the course considerably especially around a phase angle of 180°(π). Fig.20 is added as an example, showing the relative positions of the tone pips around 180° with partial cancellation (upper trace: tone pips being in phase identically, ↑↑) and with total cancellation (bottom trace: tone pips being in phase oppositely, ↑↓). Fig.19 and Fig.20 show clearly that cancellation of tone pips set off in phase oppositely will effect the clearest attenuation. Theoretically, the sensation of those signals can be brought to an auditory null, which was indeed experienced by the test subjects.

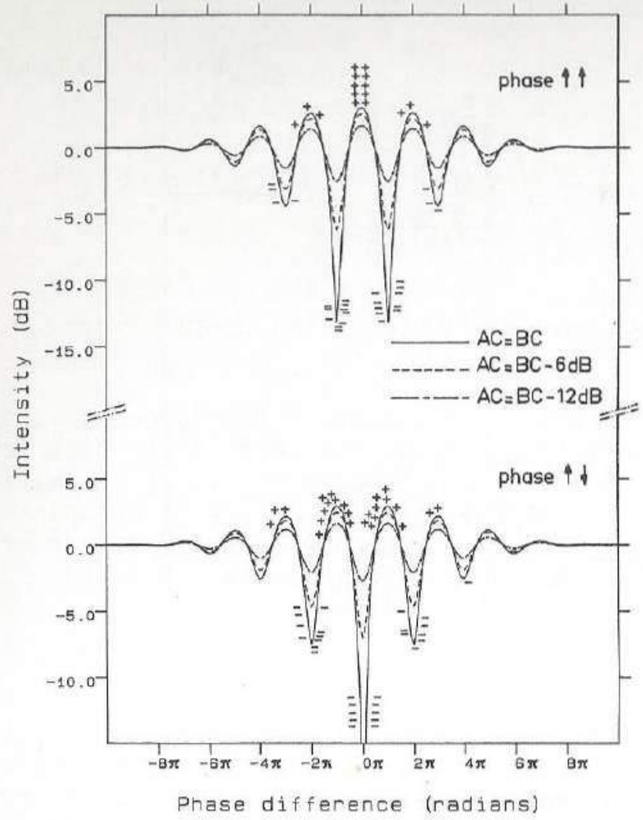

Fig.19. The graphic mathematical displays of the energy contents for 3 different amplitude ratios produced by partially overlapping tone pips, set off in phase either identically (↑↑) or oppositely (↑↓). The individual data points, indicating maximal (+) and minimal (-) loudness variations are shown. X-axis presents the phase angle in radians between the 2 signals. Y-axis presents the energy contents in dB. AC, air conduction; BC, bone conduction.

Fig.19 shows that for both tone pips set off in phase identically the maximal loudness sensation is indicated by all subjects accompanied by two minimums on either side. The individual data points for maximal and minimal loudness sensations (+/-) are shown.

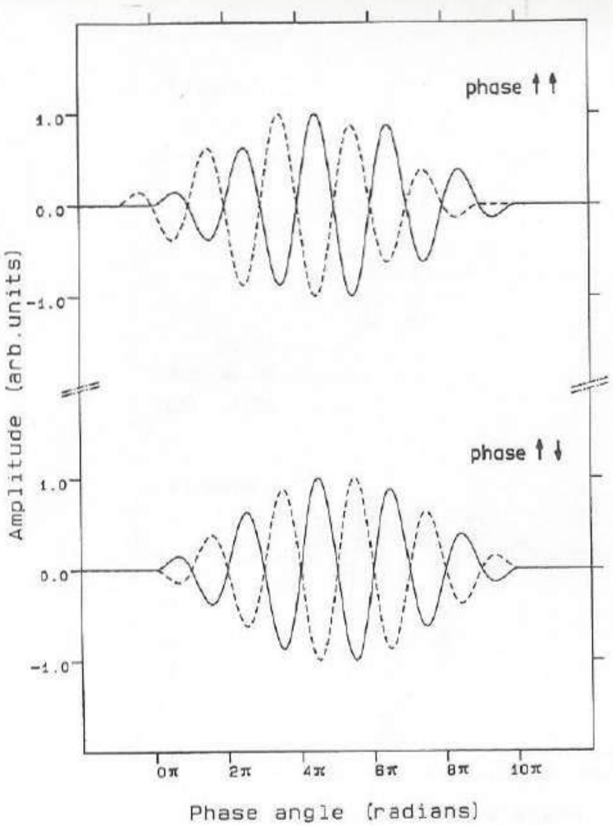

Fig.20. The relative positions of the tone pips around 180°. ↑↑, phase being identically; ↑↓, phase being oppositely. X-axis presents the phase angle in radians between the 2 signals. Y-axis shows of both signals the amplitudes in arbritary units.

The estimation of these data points is shown in table 7 for 3 time lags, as these were indicated by all subjects. The same data are shown for tone pips set off in phase oppositely.

The intensity adjustment (mean±SD) for the BC signal was 59.6±0.7 dB, for the AC signal 52.5±3.5 dB. The difference between them was 7.1±3.8 dB. Furthermore we verified the time lag, leading to the clearest dip in sensation, with BEP by selecting a rarefaction polarity for the AC tone pip and a condensation polarity for the BC tone pip. Table 7 shows these data in msec (mean±SD). The time lags obtained from all subjects with similar signals by cancellation as well as by BEP show a close relation by which no significant differences were found (P>0.1, Wilcoxon's signed rank test). Table 7 shows further the phase adjustments in degrees (mean±SD) of the continuous tones during cancellation. Dividing each individual value by 360° and next multiplying by 0.5 msec (cycle time) gives the phase angle converted into msec for continuous tones shown in table 7.

Table 7.-Time lags in msec (mean ± SD) between bone and air conduction signals

		cancellation impulse	BEP	cancellation continuous
↑↑	min	0.66 ± 0.15		191° ± 100°
	max	0.91 ± 0.19		0.25 ± 0.14
	min	1.17 ± 0.19		
↑↓	max	0.75 ± 0.12		
	min	0.95 ± 0.16	0.86 ± 0.10	
	max	1.25 ± 0.26		

Time lags (mean±SD) in msec between BC and AC. min., minimal loudness sensation; max., maximal loudness sensation; ↑↑, phase set off identically; ↑↓, phase set off oppositely. No significant differences were found between the data obtained by cancellation with impulse signals and by BEP elicited to similar signals (P>0.1).

Discussion

Fig.19 shows for each of the given polarity combinations a close correspondence of the psychophysical findings with those which are predicted mathematically. This is stressed by the following 2 observations. Firstly, the minimal and maximal loudness sensations obtained psychophysically are separated by about 180° for 2000 Hz (0.25 msec). Secondly, changing the polarity of the BC tone pip with 180° yields, for a given polarity combination, to a opposite sensation, i.e., in our case a change from a maximal to a minimal sensation. Finally, the physical verification with BEP of the time lag associated with the clearest dip in sensation attributes in this respect. We found in an earlier study with BEP (Boezeman et al. 1983) a time lag of 0.88 msec. In that study signals with similar polarity (rarefaction) were used, which appears to coincide very well with the psychophysical results (0.91 msec) found herewith. The results associated with the use of continuous tones are more complicated. The SD of the phase adjustments presented in degrees is quite high, an observation, which we found earlier for 4000 Hz (Kapteyn et al. 1983). The phase angles converted into msec show values which are quite less than those found either psychophysically with impulse signals or physically with BEP. As mentioned before, the phase readings may contain an undetectable shift of 360°, i.e., one or more cycles may be involved. If our findings are summated with about 0.5 msec (cycle time) the results would be in agreement with those which we found experimentally.

Considering the intensity adjustments of the impulse signals we have found an attenuation of the BC signal of about 7 dB. That implies an attenuation of the signal with distance, i.e., when the vibrator is placed onto the frontal bone instead of onto the mastoid process. This is in agreement with the threshold measurements made earlier for continuous signals by Dirks and Malmquist (1969) and for impulse signals by Boezeman et al. (1983).

Our findings strongly suggest that the air input leads the bone input with about 0.9 msec when the vibrator is situated on the frontal bone. That implies a traveling time for the BC signal to reach the inner ear which exceeds that of an air-borne sound. Our preliminary results using impulse signals of 500 Hz with similar envelopes showed that the time lag of the BC signal was increased and was transferred

in the time domain of about 2.0 msec, whereas similar signals of 4000 Hz took approximately the same values as found for 2000 Hz. These preliminary findings for 500 Hz suggest a lower velocity of sound for low frequencies transmitted along the skull. As put forward in a summarizing paper by Tonndorf (1976) dealing with bone conduction, the speed of propagation of vibratory energy transmitted along the flat bones of the skull is variously and relatively low, ranging from 100-800 m/sec. However, vibratory transmission through the base of the skull appeared to be much higher, i.e., up to 2600 m/sec (Wigand et al. 1964), indicating that various skull displacements are involved with the rate of propagation to different extents. Our preliminary results associated with mastoid placement of the vibrator revealed for 2000 Hz no clear tendency for the air input to lead the bone input. The time lag was found to be nil. In case of 500 Hz stimulation there remained a time lag of about 1.5 msec. These preliminary findings infer once more that there are delays involved with bone conduction stimulation, each depending upon the location of the vibrator on the head. Furthermore, it brings up the question whether the traveling speed of vibratory energy is frequency dependent. Apart from this, the influence of middle ear contribution should be considered in hearing by bone conduction for different frequencies (Tonndorf 1966) on which a prolonged study is focused. In conclusion, the cancellation method provides accurately the phase relation and amplitude ratio between bone and air conduction pathways. Furthermore, it is very suitable in research on humans for being a non-invasive approach.

CHAPTER 8

SUMMARY

Chapter 1 presents the introduction of the topic investigated in this study, i.e., the assessment of hearing loss in an objective manner. It formulates successively the questions and problems associated with it.

Chapter 2 arranges the literature on brainstem auditory evoked potentials as far as it concerns its application in audiology, and also supplies background information for a better understanding of the issue, which yielded to the problem definition set forth.

Chapter 3 describes the method of recording evoked potentials elicited to bone and air conduction stimuli in subjects with normal hearing. It emphazises the importance of a carefully selected stimulus for transmission to the bone vibrator and earphone. A 2000 Hz tone pip provides an acceptable spectral similarity between the acoustic outputs from both stimulators. Latency values of both responses show a discrepancy between bone and air conduction channels. Compared to the air conduction response the bone conduction response shows a time lag of about 0.9 msec. Mechanisms possibly explaining this result are discussed, of which one cause is put forward in all likelihood. It concerns, in the case of frontal bone stimulation, the increased traveling time needed for the bone conduction stimulus to reach the inner ear along the skull.

Chapter 4 sets forth an essential issue in clinical audiology. It considers the need of masking the untested ear without simultaneous masking of the ear under investigation. Therefore masking techniques are applied to a group of subjects with normal hearing to investigate the influence of narrow band masking on the latencies of brainstem auditory evoked potentials. The levels of sufficient masking and overmasking are determined. Furthermore, it considers the phenomenon of central masking of which its influence on the central conduction times of these responses is investigated.

No clear effect has been noticed and therefore the influence of central masking can be ignored in clinical practice if masking of the untested ear is necessary.

Chapter 5 marks out a different approach for the assessment of hearing loss. It deals in a novel way with the introduction of the cancellation method. The possibilities are described for its application in clinical practice as well as the fundamental problem of calibrating bone vibrators which latter issue is still debated up to now.

Chapter 6 evaluates the application in clinical practice of both the cancellation method and brainstem auditory evoked potentials. It incorporates the findings of the preceding chapters 3, 4 and 5. 24 patients with unilaterally mixed hearing disorders have been investigated, of whom 18 have been submitted for operation on middle ear structures. The cancellation method has a stronger relationship with pure tone audiometry than evoked brainstem potentials in predicting the air-bone gap. This stems from the fact that the cancellation metod is not affected by a recruitment-like phenomenon such as a rapid increase of loudness. An observation which is in contrast to the findings with brainstem auditory evoked potentials. The results of evoked responses elicited to bone and air conduction signals show therefore an underestimation in the prediction of the actual audiometric data. The additional use of evoked responses elicited to bone conduction stimuli favors the estimation of the air-bone gap. The cancellation method can further be applied to assess the functional balance between both inner ears, especially useful when dealing with severe bilaterally conductive hearing loss, in which case both pure tone audiometry and evoked responses mostly fail. Finally, combining the cancellation technique with brainstem potentials elicited to air conduction stimuli simultaneously permits the estimation of the cochlear reserve without the need of bone conduction stimulation. This will make appropriate masking of the untested ear, if needed, far less troublesome.

Chapter 7 is devoted to the time lag observed between the

bone and air conduction responses shown in chapter 3. The proposition set forth in chapter 3 is extended fundamentally. In that respect the use of the cancellation method with impulse signals is advantageous as the phase assessment between the bone and air conduction signal is computer-assisted. The phase lag found with this set-up corresponds with the results mentioned before in chapter 3. These psychophysical findings are once more verified in an objective manner with brainstem potentials elicited separately to similar signals. Therefore the findings shown in chapter 3 and in chapter 7 strongly suggest a traveling time for the bone conduction signal to reach the inner ear, which exceeds that of an air-borne sound. Preliminary results indicate that in the case of mastoid stimulation the phase lag between the bone and air conduction signal is nil. This demonstrates that the phase angle between the 2 signals relies upon the location of the vibrator on the head. Furthermore it appears from our preliminary results that the phase angle most likely depends upon the frequency used and thus puts in mind the existence of different transmissions of vibratory energy reaching the inner ear along the skull.

SAMENVATTING

Hoofdstuk 1 bevat de introductie van het onderzoeksobject van deze studie: namelijk de vaststelling van de slechthorendheid volgens een objectieve methode. De vraagstelling wordt geformuleerd en de problemen, die daarmee samenhangen, worden uiteengezet.

In hoofdstuk 2 wordt de literatuur gerangschikt, die betrekking heeft op auditief opgewekte hersenstampotentialen, voor zover die van toepassing zijn op het terrein van de klinische audiologie. Tevens wordt achtergrondinformatie verstrekt om een beter inzicht te verkrijgen in het onderwerp, dat voerde tot de reeds vermelde probleemstelling.

Hoofdstuk 3 bevat de methoden en technieken voor de registratie van hersenstampotentialen, opgewekt door auditieve stimuli, enerzijds via de beengeleiding anderzijds via de luchtgeleiding. De nadruk wordt gelegd op de gelijkvormigheid van de spectrale inhoud van het akoestische been- en het lucht-geleidingssignaal. Een sinusvormig impuls-signaal van 2000 Hz, gedurende 5 perioden, voldoet hieraan. De latentie waarden van beide responsies laten een discrepantie zien. Als de response verkregen door luchtgeleiding wordt vergeleken met die van beengeleiding leidt dat tot een tijdsverschil van ongeveer 0.9 msec. In dit hoofdstuk wordt verder ingegaan op de mogelijke oorzaken hiervan. Hoogstwaarschijnlijk is de oorzaak, dat, in geval van beengeleidingsstimulatie op het voorhoofd, het geleidingssignaal een langere looptijd heeft dan het luchtgeleidingssignaal om het binnenoor te bereiken.

In hoofdstuk 4 wordt een belangrijke kwestie in de klinische audiologie besproken. Het gaat om de noodzaak van maskering van het niet te onderzoeken oor zonder gelijktijdige maskering van het wel te onderzoeken oor. Voor dit onderzoek zijn maskeertechnieken toegepast bij proefpersonen met een normaal gehoor. De invloed van maskering op de latenties van auditief opgewekte hersenstampotentialen is onderzocht. De niveaus van voldoende maskering en overmaskering zijn

vastgesteld. Tevens is de invloed van centrale maskering op bovengenoemde latenties onderzocht. Voorts wordt beschouwd de invloed van centrale maskering op de centrale geleidingstijden van deze responsies. Daarbij is geen duidelijk effect gebleken en er behoeft dus geen rekening gehouden te worden met de invloed van centrale maskering, indien maskering van het niet te onderzoeken oor noodzakelijk is.

In hoofdstuk 5 wordt een andere benadering besproken voor de vaststelling van slechthorendheid. Namelijk: de introductie van de "cancellation"-methode. De mogelijkheden voor toepassing in de klinische praktijk worden besproken, zowel als het fundamentele probleem om beengeleiders te ijken. Dit laatste is tot heden volop in discussie en is derhalve ook nog niet internationaal gestandaardiseerd.

In hoofdstuk 6 wordt de klinische toepassing onderzocht van zowel de "cancellation"-methode als de door auditieve prikkels opgewekte hersenstampotentialen. Er wordt gebruik gemaakt van de bevindingen in de voorafgaande hoofdstukken 3, 4 en 5. Vierentwintig patienten met eenzijdige gemengde gehoorverliezen zijn onderzocht, waarvan 18 patienten zijn geopereerd aan het middenoor. De "cancellation"-methode voorspelt het gehoorverlies, zoals te zien in het audiogram, accurater dan het gebruik van opgewekte hersenstam potentialen. Dit is gebaseerd op het feit, dat de "cancellation"-methode niet wordt beinvloed door een abnormaal snelle toename van de geluidssterkte van de aangeboden stimulus. Een waarneming, die in tegenstelling is tot de bevindingen met auditief opgewekte hersenstam potentialen. Door dit verschijnsel kan een gehoorverlies door het op bovendrempelig niveau gebruiken van bovengenoemde potentialen ondergewaardeerd worden. Het additionele gebruik van een beengeleider naast een hoofdtelefoon begunstigt de bepaling van een "air-bone gap". De "cancellation"-methode kan verder worden toegepast om de functionele balans van de gehoorscherpte tussen beide binnenoren vast te stellen. Dit is met name van belang bij dubbelzijdige geleidingsverliezen, in welk laatste geval de audiometrie en bovengenoemde hersenstampotentialen meestal tekort schieten. Tenslotte: de combinatie van de "cancellation"-methode simultaan met hersenstampotentialen opgewekt door auditieve prikkels via de luchtgeleiding, laat een meting toe van de gehoorsscherpte van het binnenoor zonder gebruik te maken van beengeleidingsstimulatie. Dit maakt maskering van het niet te onderzoeken oor -indien noodzakelijk- beduidend minder gecompliceerd.

Hoofdstuk 7 is gewijd aan het tijdsverschil dat aanwezig is tussen beide responsies, zoals in hoofdstuk 3 uiteengezet. In dat opzicht wordt het onderzoek ter verklaring van bovenstaand fenomeen fundamenteel uitgebreid. De "cancellation"-methode met impuls-signalen blijkt goed bruikbaar, daar de faseïnstelling tussen het been- en het luchtgeleidingssignaal exact bekend is vanwege de berekening door de computer. Het tijdsverschil, gevonden met deze methode, komt overeen met de resultaten vermeld in hoofdstuk 3. Deze psychofysische bevindingen worden geobjectiveerd met hersenstampotentialen, afzonderlijk opgewekt door dezelfde signalen. De bevindingen vermeld in de hoofdstukken 3 en 7 wijzen daarom sterk in de richting van een looptijd voor het beengeleidingssignaal, die langer is dan die van een luchtgeleidingssignaal. Voorlopige resultaten tonen aan, dat, in het geval van mastoïed-stimulatie, het tijdsverschil tussen been- en luchtgeleiding te verwaarlozen is. Verder blijkt dat de fasehoek tussen de twee signalen berust op de locatie van de beengeleider op het hoofd. Onze voorlopige resultaten geven aanwijzingen dat de fasehoek hoogstwaarschijnlijk afhankelijk is van de gebruikte frequentie en vragen onze aandacht voor het bestaan van verschillende wegen in de schedel om de trillings-energie naar het binnenoor over te brengen.

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GLOSSARY

Air-Bone Gap — The air-bone gap is the difference in decibels between the hearing threshold levels of the air and bone conduction system for a particular frequency.

Air Conduction (AC) — Air conduction is the process by which sound waves are conducted to the inner ear through the outer ear canal and the middle ear. The AC sensitivity is normally tested with a headphone.

Audiogram — An audiogram is a graph that shows hearing threshold level as a function of frequency.

Bone Conduction (BC) — Bone conduction is the process by which sound waves are conducted to the inner ear through the cranial bones. The BC sensitivity is tested with a bone vibrator normally placed on the mastoid process.

Conductive Hearing Loss — The sound energy reaching the inner ear by air conduction is reduced by disturbances in the acoustic transmission located in the outer or middle ear.

Hearing Threshold Level (HL) — This is the difference, expressed in decibels of the threshold of the relevant ear at a specified frequency and a standard reference zero level for that frequency as defined in pure tone audiometry. Practically it is the reading in decibels, on a standard audiometer, that corresponds to the listener's

hearing threshold.

Interpeak Latency (IPL) — The latency measured between two relevant positive peaks in the brainstem evoked response.

Mixed Hearing Disorders — A combination of conductive and sensory-neural hearing loss.

Peak Latency (PL) — The latency measured from stimulus onset to the positive peak of the relevant wave in the brainstem evoked response.

Recruitment — The recruitment of loudness is an abnormally rapid increase in sensation as a function of the sound-pressure level of a pure tone presented to the ear at supra-threshold level.

Sensation Level (SL in dB) — The sensation of a sound applied corresponding the relevant number of decibels above the individual's threshold.

Sensory-neural Hearing Loss — A hearing impairment based on the abnormality of the sense organ, the eight nerve, the central auditory pathways or a combination of them.

Shadow Hearing — The not meant perception of a sound, presented via a headphone to one ear at high intensity, in the contralateral ear caused by the bone conduction mechanism.

Sound Pressure Level — This is the ratio, expressed in decibels, of the effective sound pressure (root-mean-square) of a particular tone or noise to a standard reference pressure. The reference pressure in common use for air-borne sound is 0.0002 dyne per square cm.

VRIJE UNIVERSITEIT TE AMSTERDAM

"THE ESTIMATION OF THE BONE AND AIR CONDUCTION THRESHOLDS USING BRAINSTEM AUDITORY EVOKED POTENTIALS AND CANCELLATION TECHNIQUES."

AN EXPERIMENTAL AND CLINICAL STUDY

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van
doctor in de geneeskunde
aan de Vrije Universiteit te Amsterdam,
op gezag van de rector magnificus
dr. P.J.D. Drenth,
hoogleraar in de faculteit
der sociale wetenschappen,
in het openbaar te verdedigen op
vrijdag 16 december 1983 te 13.30 uur
in het hoofdgebouw der universiteit,
De Boelelaan 1105

door

EDUARD HENRI JAN FELIX BOEZEMAN
geboren te Hulst

Academische Pers
Amsterdam

Promotor: Prof. dr S.L. Visser
Copromotor: Dr T.S. Kapteyn
Referent: Prof. dr L. Feenstra

STELLINGEN

1. Het verdient aanbeveling bij de toepassing van electrische response-audiometrie de gebruikte stimuli niet alleen fysisch maar ook psycho-fysisch te ijken.

2. Het tijdinterval tussen het moment van aanbod van een toon via een beengeleider geplaatst op het hoofd en de perceptie ervan in het binnenoor hangt niet alleen af van de plaats van de beengeleider, maar hoogstwaarschijnlijk ook van de frequentie van de toon.

3. Het gebruik van een beengeleidingsstimulus naast de luchtgeleidingsstimulus in de electrische response-audiometrie vergroot de diagnostische mogelijkheden van deze meetmethode.

4. Bij toepassing van zowel been- als luchtgeleidingsstimulatie in de electrische response-audiometrie dient aandacht besteed te worden aan de spectrale gelijkvormigheid van beide acoustische signalen, alvorens de resultaten aan elkaar te relateren.

5. Door het bewerkstelligen van een spectrale gelijkvormigheid van de acoustische lucht- en beengeleidingssignalen in de electrische response-audiometrie is, bij aanbod via de hoofdtelefoon op het oor respectievelijk via de beengeleider op het voorhoofd, het te constateren verschil in latentie niet op te heffen.

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

6. Hoewel contralaterale maskering bij auditief opgewekte hersenstampotentialen geen aantoonbare effecten van centrale maskering veroorzaakt, kan op grond daarvan een betrokkenheid van de hersenstam bij centrale maskering niet worden uitgesloten.

7. In geval van een ernstig, dubbelzijdig geleidingsverlies verdient ter vaststelling van de grootte van de "air-bone gap" de "cancellation"-methode de voorkeur boven de toonaudiometrie.

8. De presentatie van het idee, dat door middel van hersenstampotentialen opgewekt via de beengeleiding de cochleaire functie van een oor kan worden gemeten zonder de noodzaak van maskering, getuigt van gebrek aan inzicht in het mechanisme, dat het "overhoren" veroorzaakt. De grondgedachte is slechts dan juist, indien de verkregen response "near field" is geregistreerd.

Glasscock, M.E., Jackson, C.G. and Josey, M.S. In: J.L. Northern (Ed.), Brain Stem Electric Response Audiometry. Thieme-Stratton Inc., New York, 1981: 94-95.

9. Zowel de diepe als de oppervlakkige tak van de nervus ulnaris in de hand dient electromyografisch te worden onderzocht bij patienten met de zogenaamde "cyclist palsy".

10. Hoewel de functionele eigenschappen van het brein beïnvloed worden door organische afwijkingen, zijn deze laatsten niet het doel van het EEG-onderzoek. De te onderzoeken en beantwoorden vraag is: wat zijn de functionele mogelijkheden van het brein, ondanks een organische afwijking.

11. In een zeer klein percentage van patienten met epilepsie kan het EEG-onderzoek tijdens lichtflitsen bepaalde epileptische functiestoornissen aantonen. Toepassing van lichtflitsprikkeling is echter vooral een onderzoek naar de belastbaarheid van bepaalde hersensystemen t.a.v. hun vermogen tot verwerking, adaptatie en stabiliteit. Het geeft vrijwel bij elke onderzochte patient informatie en verdient daarom veel meer belangstelling.

12. Het in één categorie samenvoegen van patienten met insufficiëntie van het vertebro-basilaris systeem, zoals veelal in klinische "trials" geschiedt, is zinloos en leidt niet tot een optimale diagnostiek en therapie van deze pluriforme aandoening.

13. Het is gewenst, het rendement van de alternatieve geneeswijzen te vergelijken met dat van de gevestigde gezondheidszorg waar het de kosten betreft.

14. Zonder wijziging van het huisvestingsbeleid zal de binnenstad van Amsterdam meer en meer een enclave voor welgestelden worden.