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The prediction of hearing thresholds with dichotic Multiple Frequency Steady State Evoked Potentials compared to an Auditory Brainstem Response protocol

by

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University of Pretoria, Pretoria.

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"What we see now is like a dim image in a mirror; then we shall see face to face. What I know now is only partial; then it will be complete – as complete as God's knowledge of me. Meanwhile these three remain: faith, hope and love; and the greatest of these is love". 1 Corinthians 13:12-13

Dedicated to Professor Brenda Louw and my mother, Maryna Clarke

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Summary

Title: The prediction of hearing thresholds with dichotic Multiple Frequency Steady State Evoked Potentials compared to an Auditory Brainstem Response protocol.

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Even though a test battery approach is necessary to assess auditory function on several levels for hearing assessment, the pure tone test is considered the most time efficient, accurate tool to profile hearing at barely audible levels as a function of frequency in the co-operative patient. There are, however, patients unable to co-operate under standard testing conditions, in which case, the pure tone test is rendered useless or incomplete. Subsequently, objective testing procedures such as evoked potentials are utilized to categorize hearing across the severity and configurations of hearing loss and are defined as testing procedures that require no voluntary response from the patient.

The Auditory Brainstem Response test protocol (ABR) is generally accepted as the most commonly used evoked potential technique utilized in the categorization of hearing across a frequency spectrum when conventional testing is invalid. Recently a new evoked potential technique has been developed, the dichotic Multiple Frequency Auditory Steady State Evoked Potential (Mf ASSEP). For audiometric purposes, SSEP have some advantages over ABR. However, no comparison

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between the Mf ASSEP and other evoked potentials that are currently used with high frequency, such as the ABR, has been attempted (Sininger & Cone-Wesson, 2002).

The aim of the study was to determine the validity and accuracy of dichotic Mf ASSEP for use in predicting hearing status in comparison to the Gold Standard of pure tone audiometry as well as the evoked potential standard of auditory brainstem response (click and tone burst at 500 Hz stimuli) in a group of normally hearing and a group of adolescents with hearing loss. Pure tone air conduction thresholds between 500- 4000 Hz were predicted with the Mf ASSEP technique and ABR. Furthermore, the duration of testing for each procedure was calculated.

Results indicated that the Mf ASSEP could predict pure tone thresholds between 500-4000 Hz irrespective of severity, or particular configuration of hearing loss across the frequency spectrum more accurately, and with more frequency specificity, when compared to the ABR protocol. The procedure was also more time efficient and objective. The Mf ASSEP technique could not, however, provide additional diagnostic information of neural synchrony such as is possible with the Auditory Brainstem Response. It was, therefore, concluded that both procedures should be included in test batteries, specifically when used with difficult-to-test populations, as each provides unique information of particular importance to the audiologist attempting to predict hearing in difficult-to-test populations.

Key words: Evoked potentials, auditory brainstem response, dichotic multiple frequency auditory steady state evoked potential, difficult-to-test populations, degree of hearing loss, configuration of hearing loss, objective, frequency specificity.

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Opsomming

Titel: Die voorspelling van gehoordrempels met digotiese Veelvuldige Frekwensie Standhoudende Ouditiewe Potensiale in vergelyking met 'n Ouditiewe Breinstam Respons protokol

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Ten spyte van die feit dat 'n toetsbattery benodig word om ouditiewe funksionering op verskeie vlakke van gehoorevaluasie te bepaal, word die suiwertoontoets tans steeds beskou as die mees tyd-effektiewe en akkurate metode om gehoor, as 'n funksie van frekwensie, by net-hoorbare intensiteite te peil by die samewerkende pasiënt. Daar is egter sommige pasiënte wat nie die nodige samewerking kan verskaf tydens standaard oudiometriese toetsing nie, en sodoende die effektiwiteit van die suiwertoontoets merkbaar verswak. Gevolglik word objektiewe prosedures, soos ontlokte potensiale, wat geen willekeurige respons van 'n pasiënt vereis nie, benut om hoorvermoëns ten opsigte van graad en komfigurasie te kategoriseer.

Die Ouditiewe Breinstam Respons toetsprosedure (OBR) word huidiglik algemeen aanvaar as die mees algemeen gebruikte ontlokte potensiaaltegniek tans in gebruik vir die kategorisering van gehoor oor die frekwensie spektrum wanner konvensionele toetsing onbetroubaar is. Daar is egter in die afgelope aantal jare 'n nuwe ontlokte potensiaal tegniek beskryf, die digotiese Veelvuldige Frekwensie Standhoudende Ontlokte Potensiaal. Vir oudiometriese doeleindes het die standhoudende response sekere voordele bo die OBR. Geen direkte vergelyking is

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egter tot op datum gemaak tussen die standhoudende ontlokte potensiaal tegniek en die ander ontlokte potensiaal tegnieke wat tans algemeen gebruik word soos die OBR, nie.

Die studie het ten doel gestel om die geldigheid en akkuraatheid van die digotiese veelvuldige frekwensie stanhoudende ontlokte potensiaal te bepaal in vergelyking met die Goud Standaard van suiwertoonoudiometrie, asook die ontlokte potensiaal tegniek van OBR (klik en toonpols by 500 Hz as stimuli) by 'n groep normaalhorende persone sowel as persone met gehoorverlies. Daar is gepoog om suiwertoonluggeleidingdrempels tussen 500- 4000 Hz tes voorspel met die Veelvuldige Frekwensie Standhoudende Ontlokte Potensiaal en 'n OBR protokol. Die duur van elke toetsprosedure is telkens bereken.

Die resultate het aangetoon dat die Veelvuldige Frekwensie Standhoudende Response in staat was om suiwertoondrempels tussen 500-4000Hz meer akkuraat, en met verhoogde frekwensie-spesifisiteit te voorspel,ongeag van die graad van verlies of die verloop van die oudiogram, in vergelyking met die OBR protokol. Die prosedure was ook meer tydeffektief en objektief. Die Veelvuldige Frekwensie Standhoudende Ontlokte Potensiaal kon egter nie addisionele diagnostiese inligting oor neurale sinkronisasie verskaf nie, 'n parameter wat wel deur die manipulasie van die klik-ontlokte OBR moontik is. Op grond hiervan word voorgestel dat beide tegnieke ingesluit behoort te word in toetsbatterye, ten einde elkeen se unieke bydrae te benut, veral in drempelbepaling in moeiliktoetsbare populasies.

Sleutelwoorde: Ontlokte potensiale, ouditiewe breinstam respons, digotiese veelvuldige frekwensie ouditiewe stanhoudende ontlokte potensiaal, moelik toetsbare populasies, graad van gehoorverlies, konfigurasie van gehoorverlies, objektief, frekwensie spesifiek.

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Appendix B – ABR data analysis for threshold estimates

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List of abbreviations

ABR	Auditory Brainstem Response
ABR TB	Auditory Brainstem Response with Tone Burst
AEP	Auditory Evoked Potentials
AM	Amplitude Modulation
ASSEP	Auditory Steady State Evoked Potential
BAEP	Brainstem Auditory Evoked Potential
BAER	Brainstem Auditory Evoked Response
CM	Cochlear Microphonic
dB	Decibel
EEG	Electroenchephalogram
EcochG	Electrocochleography
EP	Evoked Potential
FFT	Fast Fourier Transform
FM	Frequency Modulation
HL	Hearing Level
Hz	Hertz
kHz	kilo Hertz
LLR	Late Latency Response
MF ASSEP	Multiple frequency Auditory Steady State Evoked Potential
MLR	Middle Latency Response
MM	Mixed Modulation
MRL	Minimum Response Level
msec	Milliseconds
nHL	Normal Hearing Level
OAEs	Oto-Acoustic Emissions
PT	Pure tone
PTA	Pure tone Average
PTTs	Pure tone thresholds
SD	Standard deviation
SLRs	Short latency responses
SPL	Sound Pressure Level
SS	Steady State
SSEP	Steady State Evoked Potential
SSR	Steady State Response

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CHAPTER ONE

PROBLEM STATEMENT AND RATIONALE FOR THE STUDY

Aim of Chapter

The rationale for the study is presented within the context of diagnostic audiometry for difficult-to-test populations.

1.1 INTRODUCTION

"Omnes homines naturaliter sure desiderant"

All men naturally desire to know

The form and function of the hearing mechanism have captured the imagination of artists and scientists through the ages. From the scientific perspective, the discipline of **Audiology**, derived from the Latin root *audire* (to hear) and the Greek suffix *logos* (the study of), essentially encompasses the exploration of normal and abnormal hearing across a wide span of populations. Early reports of such endeavors date back as far the writings of Aristotle: ("*Those who are born deaf all become senseless and incapable of reason*") and Plato: ("*men expend fruitless labor, just as they do in astronomy, in measuring audible tones and chords*"). From these statements, the two main streams of audiology can be derived, namely, rehabilitative audiology concerned with the management of the person with hearing loss, and diagnostic audiology concerned with the categorization of hearing as normal or abnormal within selected parameters. The latter is the focus of this text. Novak & Schier coined the term 'audiologist' in the 1930s. It referred to persons responsible for hearing aid fitting. It was not until the end of World War II, with the return of thousands of veterans in need of diagnostic and rehabilitative services, including hearing services, that **audiology centers** emerged in a variety of settings such as hospitals, private institutions and universities (Martin, 1986). "*Such was*

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part of the legacy we inherited when the science of modern audiology began more than four decades ago" (Martin, 1986:15).

More than 15 years have passed since the above statement was made and, in retrospect, prolific researchers like Jerger, Carhart and their peers have wrought changes that, in the words of Luterman (1986:249) were *"previously conceived as unattainable flights of fantasy"*. Some of the diagnostic panaceas have come and gone, usually because they have been replaced with automated and combination computerized versions of previously manual procedures. Audiology too, has been touched by the powerful hand of technology. Even though benchmark activities have occurred in diagnostic audiology, and their effects have aided enormously in understanding hearing ability, certain things remain unresolved. In some ways the field of audiology is facing uneasy times, as *"at the present time and the foreseeable future engineering (technological) capabilities will far exceed our capacities to exploit them clinically"* (Ross, 1986:36; parentheses mine).

Amid the constant flux between the novel and the traditional, the pure tone test still stands firm, as it did in the early days, as the cornerstone of hearing assessment (Katz, 2002). The pure tone audiogram remains the starting point to the entire diagnostic process, as well as the transitional point from which diagnostics moves into the rehabilitative domain.

The voluntary motor response to a pure tone, indicating that sound was perceived, is however, unattainable in some of the populations that audiologists serve. These persons are considered, for a variety of reasons, as difficult-to-test. The purpose of this chapter is to delineate the procedures, and their rationales, implemented within these so-called

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difficult-to-test populations in diagnostic audiology. Their characteristics will be described, followed by an outline of the existing thought processes and procedures that govern current practice. Issues that relate to the inferential nature of current hearing assessment and the test battery approach are addressed with attention to the crosscheck in audiometric results.

This will serve as a logical introduction to the so-called objective testing methods, the role of which changes from that of substantiation (with objective testing as a strong crosscheck) to serving as the primary tool in estimating hearing acuity in cases where voluntary responses to sound are inconclusive or inaccurate.

The Auditory Brainstem Response (ABR) test procedure is generally described as the standard evoked potential technique utilized in the categorization of hearing across a frequency spectrum when conventional testing is invalid. The most persistent challenges faced by the ABR will be presented, and, within this paradigm, an alternative to the ABR namely Auditory Steady State Evoked Potentials (ASSEP) is introduced, which is postulated to overcome some of the caveats of existing techniques.

1.2 THE NECESSITY FOR A TEST BATTERY AND THE CROSS CHECK PRINCIPLE IN DIAGNOSTIC AUDIOLOGY

The transformation of new discoveries into practical clinical procedures has been a frequent occurrence in audiological test development over the past three decades" (Gorga 1999:29). After three decades, there have been tremendous gains in the knowledge of the hearing mechanism in normal and pathologic ears. Advances in technology have assisted the refinement of testing procedures, and elaborate support systems have been developed to sustain these enterprises. It is somewhat astounding to

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realize the ongoing challenge of the prediction of hearing status in an era of technological innovations that profoundly and constantly influence the field of audiology.

It is then with much humility that audiologists should make two diverse but related acknowledgements. Firstly, no form of audiometric endeavor has been developed that directly measures the subject's awareness of sound (Goldstein & Aldrich, 1999). Secondly, there is no audiometric procedure that can singly infer all aspects of hearing in a consistent and adequate manner (Hall, 1992).

The audiometric process, in its true essence, remains inferential: an acoustic signal is presented, a reaction occurs based on awareness in some component of the auditory system of the person, and hearing is inferred from the reaction (Goldstein & Aldrich, 1999). This reaction can take many forms, depending on the test situation and the client. It can take the form of an involuntary change in behavior such as a startle reflex, or a response that occurs voluntarily such as the pressing of button following a signal. It may be an acoustic response from the ear itself such as an oto-acoustic emission, or a change in the electrical property of the body.

The second fact alludes to the necessity for a test battery. The rationale for the use of a variety of tests in hearing assessment is compelled by the complexity of the ear as well as by the need for the provision of responsible and effective assessment of the functioning of this complex system (Hannley, 1986). The ear can be visualized as a system comprising a series of components with distinct functions organized in a quasi-hierarchical manner from the periphery to the center (Hannley, 1986). Impairment at a peripheral level dominates the hearing profile over central impairments. The distortion placed on the auditory signal by the impairment becomes additive and multiplicative as

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sound progresses to the center, entangling symptoms as progression continues up the hierarchy. In an attempt to disentangle the constellation of symptoms, the test battery is introduced to this system to pinpoint impairment, identify co-existing disorders and provide an overview of contributions to normal and abnormal reactions to auditory stimuli.

As an extension of the test battery, the crosscheck principle is proposed. This was introduced by Jerger & Hayes (1976) to accommodate the influence of multi-level pathology on the hearing mechanism. The crosscheck principle states that single test results are not accepted as conclusive evidence of the nature, degree and site of pathology without the support of at least one additional test (Jerger & Hayes, 1976; Hannley, 1986; Bachman & Hall, 1998).

The strongest crosscheck is provided by *objective physiological test results* to verify threshold data as well as data characterizing the site and nature of pathology (Hannley, 1986:3) that remain independent of the patient's voluntary responses. The physiological test procedures counter the inherent flaws in human response, thereby minimizing the probability of an incorrect diagnosis.

At the advent of this millennium, a variety of procedures are available to determine and cross check audiometric performance. These procedures no longer only rely on the traditional, long-established, behavioral psycho-acoustic tests with pure tones and speech, but also on radiology, brainstem imaging, middle ear measures, ear canal emissions, tests of vestibular function and, specifically related to this study, evoked potential measurements. Within the test battery and cross check context, however, the gold standard for measuring hearing sensitivity continues to be the voluntary behavioral

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response of a person to pure tones as obtained in standard behavioral testing. It remains the least expensive and most definitive audiometric procedure to measure auditory thresholds as a function of frequency (Gorga, 1999; De Waal, 2000). Based on the pure tone audiogram, the presence or absence of a hearing loss can be determined and monitored over time, while the severity, degree and configuration of hearing loss can, furthermore, be quantified and managed based on the findings.

The situation does not, however, remain as clear-cut as it may sound from the previous discussion across the client populations that require hearing assessment. Because of the inferential nature of hearing assessment, audiologists are required to compensate through the utilization of a test battery based on the crosscheck principle. The following section discusses the challenge of providing accurate hearing assessment when the audiologist can no longer rely on the patient's co-operation in the pure tone audiometry setting.

1.3 DIAGNOSTIC AUDIOLOGY IN DIFFICULT-TO-TEST POPULASTIONS – INTRODUCTION TO AUDITORY EVOKED POTENTIALS

The well-known author Paul Anderson is credited with once stating:"*I have yet to see any problem, however complicated, which if you look at it the right way, did not become still more complicated*". Such is the case with populations who are unable to provide the necessary voluntary behavioral responses required for the pure tone audiogram. These populations are often referred to as "difficult-to-test–with pure tone audiometry" or, in short, "difficult-to-test". They cannot, for some or other reason, participate sufficiently in conventional testing procedures. Thus, pure tone testing is precluded and/or the results tend to be inaccurately or poorly defined. According to Balfour, Pillion & Gaskin (1998) difficult-to-test populations deal with the too young to test, too critically ill to test,

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subconscious patients, patients mentally incapable of providing co-operation, as well as subjects who refuse to co-operate. It is in the assessment of populations like these that the audiologist has to rely heavily on objective evaluation procedures. In these cases, the "*objective physiological test*" repositions itself from being a valid tool in cross checking other results to being the primary diagnostic tool in the assessment protocol (Hannley, 1986:3).

The technological development that ensured the capability to record from the scalp (namely, evoked potentials that are generated at various levels of the nervous system) has enabled a multitude of applications relevant to the assessment of the ear, hearing and components of the nervous system (Ferraro & Durrant, 1994). This development has been pivotal within the quest for an optimal, objective audiological diagnostic procedure to aid in the assessment of persons regarded as difficult-to-test with behavioral testing.

Lins et al. (1996) confirmed the above by stressing that early auditory evoked potentials, in particular the ABR, are critical and essential in threshold prediction in difficult-to-test populations. The ABR remains the logical finale in the arsenal of procedures required in the evaluation of hearing when traditional behavioral tests are precluded or their results are inconclusive (Robinette, 1994).

One of the main applications of ABR in hearing prediction is concerned with the attempt to categorize sensitivity for pure tones as normal or impaired in a similar way to the traditional behavioral audiometry and/or to gain more information regarding the site-of-lesion in diagnostic audiology. It is particularly in the categorization of pure tone

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sensitivity that the ABR is faced with challenges. The challenges will be discussed in terms of definitions and operational difficulties.

1.4 CHALLENGES FACED IN THE DEFINITION AND EXECUTION OF EVOKED POTENTIAL MEASUREMENTS

First and foremost the challenges pertain to the establishment of a clear and precise name for hearing assessment using auditory evoked potentials. Too often the term is inappropriate for what it is in the most fundamental sense. In fact, the entire field of auditory evoked potentials is burdened by hasty and confusing nomenclature and definitions. A very practical example of this, which is not directly related to this study but makes a clear point, is the use of the term *auditory neuropathy* (Starr et al., 1996).

The absence of auditory nerve function in the presence of cochlear integrity is referred to as auditory neuropathy (Hall, 2000). However, on further exploration of this unusual finding, and in recognition of case reports indicating high incidence of hiperbillirubenemia and cerebral palsy, a more appropriate term to consider would be *poli*-neuropathy with a site of lesion on the auditory nerve (Hall, 2000, italics mine). The consequences of this misnomer have implications for appropriate management. The term auditory neuropathy does not fully encompass the multidisciplinary approach required to effectively manage this type of client, while polineuropathy covertly insists on the hypothetical input of, among other professionals, a paediatric neurologist, ear nose and throat specialist and occupational therapist. The broader concept of confusing classification and definitions will be discussed in detail in Chapter 2.

Definitions aside, some of the other challenges faced by the use of auditory evoked potential have been published in papers of the eighties and nineties. Seventeen years

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ago, Kimura (1985:79) expressed concern about the abuse and misuse of the commonly used evoked potential technique, the ABR, when he stated that: *the flaws in the current evoked response practice are multitude and include such as fundamental matters as the lack of technical knowledge, limited experience in interpretation, and the absence of appropriate control values for comparison".* Although accurate estimates of low frequency (with brief tone burst stimuli) and high frequency (with click stimuli) pure tone behavioral threshold predictions can be obtained, many of these challenges have persisted:

- An ABR test is a time-consuming procedure, and it can take up to 30 minutes to obtain a single ABR threshold at one ear (Weber, 1994).
- Investigators have attempted many techniques to gain reliable and frequency specific hearing predictions through the use of masking and filtering paradigms. The knowledge about and the availability of these filters and attenuators in most clinical settings are limited and the tone burst is unmasked in most facilities (Balfour et al., 1998).
- The demand for technical waveform manipulation and the availability of the software to generate the latest generation sophisticated stimuli are not clearly evident in clinical practice, not to mention the extremely high cost involved in obtaining the software (Hyde, 1991; Gorga, 1999).

Gorga (1999) expresses concern about the situation when he declares that, whatever the reasons for the lack of utility of the masking and filtering techniques, whether lack of knowledge or the cost involved, the damage is ultimately inflicted on the patient. Poor and inaccurate diagnostic procedures would surely result in sub-standard recommendations regarding the rehabilitation of the disorder. The value of increased

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knowledge about these techniques would be to ensure that the patients would benefit from the sensitivity provided by such techniques (Gorga, 1999).

1.5 PURPOSE OF THE STUDY

As with most scientific endeavors, the search for increased knowledge has diverged into other techniques. One of most recent undertakings to obtain frequency specific objective hearing threshold predictions, without some of the problems facing ABR, is the amplitude modulated Steady State Response, or Frequency Following Response to tonal stimuli (Kuwada, Batra & Maher, 1986). This technique employs a continuous tone, amplitude-modulated at a frequency that provokes a Steady State Response at the frequency of modulation (Chambers, Feth & Burns, 1986; Rickards & Clark, 1984). For audiometric purposes, ASSEP have some advantages over ABR, such as:

- The measurement is an example of true objectivity. Automated response detection is used in the frequency domain and therefore neither peaks nor troughs need to be identified in the time domain. No response is required from the patient and no interpretation is required from the researcher/ investigator (Lins et al., 1995, Perez-Abalo, et al., 2001).
- The techniques used to determine the presence or absence of a response at a specific modulation frequency to the noise at the adjacent frequencies and to assess the reliability of responses automatically are clear and precise (John & Picton, 2000).
- The ASSEP can be evoked by definite frequency specific stimuli. For example, the loss of hearing sensitivity may be independently and accurately pinpointed in the high, middle and low frequency range, and appropriate amplification may be selected for that particular hearing loss without any responses from the patient. The difficulty with the use of the ABR in this regard is that the ABR causes a greater spread of energy into frequencies other than the nominal frequency and needs masking noise

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to reduce the effect of the spectral splatter caused by the energy (Cohen, Rickards & Clark, 1991; Aoyagi et al., 1994; Rickards et al., 1994; Rance et al., 1998). The ASSEP can be recorded down to 20-30 dB above behavioral thresholds in normally hearing adults and even closer to pure tone threshold in mild-moderate hearing impairment, in any state of wakefulness or sleep (John & Picton, 2000).

- Further additional benefits include the well-established and clearly defined signal and noise estimators (Lins & Picton, 1995; Lins et al., 1996).
- According to Lins et al. (1996) the final results may also be presented as a conventional audiogram, thereby combining the vital information about the degree and nature of the traditional audiogram with the objectivity of an evoked potential – a critical benefit that cannot be provided by ABR to date.

Despite the exiting advantages postulated for the ASSEP, the collection of ear specific threshold estimates is time consuming, usually averaging about 48 recordings per subject in a population where time is usually of the essence (for example infants and other categories of uncooperative patients). Lins & Picton (1995) propose the use of multiple amplitude-modulated tones in a complex acoustic stimulus presented to each ear (Multiple frequency Auditory Steady State Evoked Potential, or Mf ASSEP). When care is taken to separate the modulation frequencies at least an octave apart for the different carrier tones, different regions of the cochlea may be stimulated simultaneously. In an acoustic envelope containing amplitude-modulated tones at 0.5, 1,2 and 4 kHz, these four frequencies may be assessed simultaneously while obtaining separate results for each of them. Moreover, the technique could include both ears provided that there is a different modulation of each ear. In such a scenario, four frequencies can be simultaneously explored in both ears reducing the procedure to approximately eight

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recordings for an entire "audiogram" (Lins & Picton, 1995; Lins et al., 1996, Perez-Abalo et al., 2001).

While this technique holds promise, clinical validation has been limited. Normally hearing adults (Aoyagi et al., 1994), well babies and small numbers of hearing impaired subjects have thus far been studied (Cohen et al., 1991; Rance et al., 1995; Rance et al., 1998; Rickards et al., 1994). One of the most exhaustive trials on hearing impairment has perhaps been published by Perez-Abalo et al. (2001) on the clinical validation of 43 hearing impaired and 40 normally hearing subjects. The study reached positive conclusions about the accuracy of the dichotic Mf ASSEP technique in predicting frequency specific hearing. The ASSEP has, therefore, not yet been compared to other short latency evoked potentials that are currently used with high frequency, such as the ABR.

The purpose of this study formulated in question format reads: How valid and accurate is dichotic Mf ASSEP as an effective, accurate and objective procedure for use in estimating and predicting hearing status in comparison to the gold standard of pure tone audiometry, and the evoked potential standard of auditory brainstem response, in a group of normally hearing persons and hearing impaired adolescents?

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1.6 FRAMEWORK OF THE STUDY

To address this question a literature review and an empirical study were undertaken. The results of this endeavor are reported in the different chapters of this text. The breakdown of this thesis is as follows:

Chapter 1:	*The rationale and purpose for the study are elucidated within the context of diagnostic audiology*

The pertinent literature is reviewed in Chapters 2 and 3 in an attempt to provide a theoretical answer to the research question posed by the study:

Chapter 2:	*The clinical utility of auditory evoked potentials in the estimation of hearing: current practice, limitations and possibilities*
Chapter 3:	*Steady State as a novel technique in the estimation of hearing*

In an attempt to answer the research question posed in Chapter 1 at an empirical level, the plan of action is defined in the following chapter:

Chapter 4:	*The research method of the study*

The research endeavors and subsequent conclusions are documented, related to the literature and presented in the remainder of the study:

Chapter 5:	*A description and discussion of results*
Chapter 6:	*Conclusion to the research*

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1.7 CONCEPTUAL ORIENTATION

A more detailed review of terms and concepts follows in Chapter 2. At this juncture, however, a conceptual orientation needs to be attempted as a referral point for the remainder of the study. Some of the existing terms will be critiqued in a hierarchical manner namely the broader concepts of audiometry, and the phenomena used in the literature to describe evoked potential measurements, concluding with terms used in a description of threshold.

1.7.1 Audiometry versus Audiology

While *audiology* relates to the field and *audiometry* to the method, many of the comprehensive texts on diagnostic audiology use the two terms interchangeably (Roeser et al., 2000; Katz, 1994). This text will make a clear distinction between the field of audiology and the method employed in hearing assessment namely audiometry.

1.7.2 Evoked Response versus Evoked potential

Hall (1992) titled his text "*Handbook of Auditory Evoked Responses*", but often refers to the phenomenon as auditory evoked potentials or AEPs. These two words are also used interchangeably by Hood (1998) and Ferraro & Durrant (1994) for example. The term 'response' is a superimposition from pure tone audiometry and has been introduced to evoked potential measurements. A stimulus is presented and a response is recorded. This is, however, an incorrect assumption when considering electrophysiological measurements. The paradigm used in the recording of brain activity based on auditory stimuli entails the extraction of small time-locked electrical peaks and troughs from background random EEG activity. Electrical activity is elicited by a *signal* and not a *stimulus*. Following the signal, a potential is measured, and not a response (Goldstein & Aldrich, 1999). The term 'stimulus' implies a perception, but, in the case of ABR and

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ASSEP, which are the two evoked potential techniques employed in the study, electrical activity is measured sub-cortically merely up to brainstem level.

The argument, furthermore, holds that the potential may be present following the signal, but that the recording techniques are not sophisticated and refined enough to be able to distinguish it from the background EEG. This text, therefore, favors the use of potential rather than response, because as Hood (2001, personal communication) suggests when a potential is perceived, the use of the word 'response' is redundant.

1.7.3 Objective testing

Although the term 'objective testing' was used in the preceding section, in keeping with current terminology in the literature, the term should be applied with some reservation. Objective testing using evoked potentials such as the ABR alludes to the bypass of patient subjectivity as a means of increasing reliability of a procedure (Jerger & Hayes, 1976; Hannley, 1986; Bachman & Hall, 1998; Hood, 1998). The use of the term objectivity in that context is partially incorrect, as it merely implies the transfer of subjectivity to the tester in terms of identification and analysis of, for instance, waveforms at threshold level. True objectivity would entail no patient or tester influence, as is possible with the ASSEP technique described later in this text.

1.7.4 Physiological testing

This is a vague and perhaps abbreviated term that is used to reflect tests that are non-behavioral in nature such as the short, middle and late latency electrophysiological responses. Yet these so-called physiological test procedures are identical to standard conventional testing in their goal of assessing the physiology of the hearing mechanism and brain to traveling sound waves. The difference relates, at a primary level, to the site

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of testing. This does not make any procedure more or less physiological than another, however. For instance, behavioral testing relates traveling sound waves to the execution of a motor behavior, while the short, middle and late latency responses stem from the eight cranial nerve and brainstem processes, the primary auditory cortices and hippocampal and related areas respectively (Ferraro & Durrant, 1994). The term objective, physiological testing is unclear. In keeping with this distinction, a brief comment on behavioral testing follows.

1.7.5 Behavioral testing

Although this author used the term behavioral testing in the preceding section in keeping with current terminology in the literature, it is not an apt term for standard conventional pure tone testing to obtain a pure tone audiogram. The rationale maintains that a motor response is elicited as a reliable indication of minimal hearing (Goldstein & Aldrich, 1999), which is correct. This implies, however, that the brain's response to sound as measured from a scalp electrode at brainstem level, is not reflective of behavior, which is incorrect. The qualitative difference is, however, whether the behavior is voluntary or involuntary, and the text will further specify pure tone testing as voluntary responses to sound. This may seem like a redundant differentiation in clinical settings, but the lack of observation of responses to sound on a continuum of behavior has hampered easy transition between conventional and specialized testing on the same behavioral continuum.

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1.7.6 Electrical audiometry (Perez-Abalo et al, 2001), evoked potential audiometry (Goldstein & Aldrich, 1999) and objective audiometry (John & Picton, 2000)

The term 'electrical audiometry' as used by Perez-Abalo et al. (2001) in reference to the ABR is confusing because "*electrical activity from the auditory nerve and brainstem, recorded as evoked potential, does not represent conscious hearing. When using ABR to estimate hearing sensitivity, one should clearly state that the ABR is not a direct test of hearing and thus cannot represent or describe true conscious hearing*" (Hood, 1998:9). The question arises then, however, as to what does represent or describe true conscious hearing? Is a motor response to sound a true representation, or speech testing or speech testing in noise? These questions are beyond the scope of this text but should be considered when employing certain terminology.

'Objective audiometry' is rejected on the basis of the previous discussion of objectivity versus transferred subjectivity, as well as on the basis of the use of audiometry. Evoked potential testing is not a test of hearing (Ferraro & Durrant, 1994; Hood, 1995, Hall & Mueller, 1997; Hood, 1998), but rather the application of techniques to test synchronous neural functioning for inferences about hearing up to a specific anatomical site.

The most tempting term to use could be evoked potential audiometry (Goldstein & Aldrich, 1999). It is a clear statement of the procedure's intent to assess hearing using scalp recordings of electrical activity generated by the auditory nerve and brainstem in an ABR example. The results obtained from this procedure do not, however, reflect hearing comprehensively. The process still deals with a secondary application of information about neural synchrony that is used to make inferences about path specific hearing, and it is therefore rejected.

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The ASSEP technique holds the biggest appeal for traditional diagnostic terminology, as the stimuli used are frequency specific, and presented in audiogram format, while retaining their objective nature. However, the ASSEP, like the ABR, was not developed with threshold estimation as its primary focus. The initial impetus for ASSEP research was the exploration of electrophysiological correlates for frequency and amplitude modulated tones and their relationship to central auditory processing. The natural progression to threshold level was a logical result (Rickards, 2002, personal communication). The clinical application of the ASSEP technique is, to date, primarily focused on hearing estimation despite its tentative, research-orientated beginnings in auditory processing. Furthermore, as a hearing estimation technique, it provides frequency specific information. Thus, it is unclear why the term audiometry may not be used in this context. Perhaps with the clinical validation of the current study, and the expected increase of reports of a similar nature in the literature, more clarity will be afforded to this conundrum.

1.7.7 Electrophysiological threshold (Perez-Abalo, 2001) versus threshold estimate (Hall, 1992; Hood, 1998; Hall, 2001)

Electrophysiological threshold is rejected on the basis of the recording limitations of our current equipment. While internal brain activity generates internal physiological noise, it may be that the so-called threshold is merely the juncture where our machines are currently able to record and extract from external and internal background noise in a non-invasive manner. The cautious option and the selection for this text is threshold estimate as it is invariably higher than the standard pure tone threshold when available and usually entails the conversion of sound pressure level and/or normal hearing level to hearing level.

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1.7.8 Selection of concepts for this study

The term 'evoked potential' is preferred to evoked response, while 'objective testing procedures' are defined as procedures that do not require voluntary response from the patient, nor does it require any analysis from the tester. 'Threshold estimate' is preferred over electrophysiological threshold in keeping with the preceding discussion while pure tone audiometry will be specified as such and not generalized as behavioral testing.

1.8 SUMMARY OF CHAPTER ONE

This chapter serves as an introduction to the challenges faced in the field of diagnostic audiology when faced with difficult-to-test populations. Despite tremendous developments in the recording of the objective responses of these populations, existing tests such as the Auditory Brainstem Response have persistent limitations. A new technique, namely the Steady State Evoked Potential, can provide solutions to some of these lingering problems. The purpose of the study, to predict hearing thresholds in normal and impaired ears using the Steady State Evoked Potential (compared to pure tone audiometry and Auditory Brainstem Response), was stated. The chapter concluded with an outline of chapters and a conceptual orientation to terminology.

The transformation of new discoveries into practical clinical procedures has been a frequent occurrence in audiological test development over the past three decades (Gorga 1999:29).

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CHAPTER TWO

THE CLINICAL UTILITY OF AUDITORY EVOKED POTENTIALS IN THE ESTIMATION OF HEARING: CURRENT PRACTICE, LIMITATIONS AND POSSIBILITIES

Aim of the Chapter

This chapter will describe the current status of evoked potentials in the estimation of hearing in difficult-to test populations.

2.1 INTRODUCTION

This chapter comments on the clinical usefulness of auditory evoked potentials (AEP) in the estimation of hearing in difficult-to-test populations. The discussion does not strive to discredit the value of AEPs and their clinical usefulness is not disputed, but will rather attempt to provide some insight into some of the clear limitations that exist in current techniques. The nature of the discussion may best be summarized by Picton (1991:3) when he stated that the " *astute clinician should know what they (AEPs) indicate, be aware of what they cannot show, and learn a little about what they might demonstrate in the future since possibilities have a habit of becoming reality*". Hyde agrees with Picton when he states that: *I would like to endorse Picton's prediction that AEPs will offer many more opportunities for functional analysis of the auditory system than are currently practiced" (Hyde: 1991:26)*. These words have a prophetic ring to them.

Since the technical capability to record evoked potentials based on EEG activity in response to an acoustic signal in the 1960s, benchmark discussions of AEPs, and more specifically the auditory brainstem responses by Sohmer & Feinmesser (1967), Jewett (1970) and Jewett and Williston (1971) have appeared. Developments in stimulus and recording techniques continued in the 1980s and since the 1990s, evoked potentials

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have become an accessible, well established clinical reality, characterized by refined techniques and interdisciplinary expansions. The recent developments concerned with auditory steady state responses, discussed in Chapter 3, and the utilization of the frequency domain, seem to have enabled the field of evoked potentials to cross new frontiers in hearing prediction, again proving the truth of Picton's words.

Chapter 2 will focus on current AEP techniques and will be organized around the three issues highlighted by Picton (1991):

- The current state of knowledge
- The limitations harnessing optimal clinical practice
- Possible solutions.

The difficult-to-test population will provide the context for the discussion, and the chapter will commence with a brief description of the population as it relates to diagnostic audiometric procedures.

2.2 DIAGNOSTIC AUIODMETRY IN DIFFICULT-TO-TEST POPULATIONS

Diagnostic audiometry is concerned with effective, efficient and accurate estimation of hearing, and the gold standard for measuring hearing sensitivity continues to be the voluntary behavioural response of a person to pure tones as obtained in standard behavioural testing. It remains the least expensive and most definitive audiometric procedure for measuring auditory thresholds as a function of frequency (Gorga, 1999; De Waal, 2000). Based on the pure tone audiogram, the presence or absence of a hearing loss can be determined and monitored over time, while the severity, degree and configuration of hearing loss can be quantified and managed based on these findings.

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There are populations; however, who are unable to provide the necessary voluntary behavioral responses required for the pure tone audiogram. These populations are often referred to as difficult-to-test–with- pure -tone-audiometry or in short, difficult-to-test. Difficult-to-test populations cannot, for some or other reason, participate sufficiently in conventional testing procedures. Pure tone testing is precluded or poorly and/or inaccurately defined. Some categories of clients that are considered difficult-to-test follow:

- Neonatal infants where results are tentative and control of the subject's state is extremely difficult
- Persons who have intellectual limitations and whose test results are unreliable
- Populations with severely restricted motor capabilities precluding overt voluntary responses
- Persons with emotional and psychological problems who have inconsistent and often erratic voluntary responses
- Persons with suspected non-organic hearing loss. Often, this type of hearing loss is investigated in compensation cases where the sponsors are sceptical of results that depend on a patient's voluntary co-operation. Hard copy evidence without active patient co-operation is required as additional corroborative data in medico-legal cases
- Persons and referring physicians occasionally question the reliability of behavioral results and the rehabilitative process may be accelerated with corroborative results
- Comatose patients
- Persons with severe bilateral conductive hearing loss creating masking difficulty
- Persons undergoing assessment for Meniére's disease to obtain responses unobtainable with behavioral testing, for example, the cochlear microphonic

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- Persons with suspected retrocochlear pathology such as an acoustic neuroma are all considered difficult-to-test conclusively with conventional behavioral audiometry (Picton, 1991; Hall, 1992; Goldstein & Aldrich, 1999).

A few important implications of the above spectrum of populations are that *most of the underlying pathologies of these patients are not age related;* even though infants and young children form the majority of cases, difficult-to-test patients may be of any age (Hall, 1992). Moreover, a *difficult-to-test patient may not present as such in the first analysis,* but during testing it may be determined that voluntary reaction to an acoustic signal is not the reaction of choice to infer hearing for a particular case (Hall, 1992; 2001). It may be the least reliable option to reach valid conclusions, or too erratic to interpret with confidence. A lack of co-operation from the patient, irrespective of cause, necessitates the use of other, more objective methods of testing and other reactions to an acoustic signal need to be explored to predict hearing acuity.

As stated in Chapter 1, difficult-to-test populations are governed by two diagnostic strategies to ensure accountable service delivery. They are the test battery approach and the subsequent crosscheck principle (Jerger & Hayes, 1976; Hannley, 1986; Bachman & Hall, 1998). Although some researchers have sought a single ideal measurement technique, others have accepted and exploited the test battery approach to greater benefit (Jerger, 1993). The test battery is introduced to accommodate the hierarchical complexity of the ear in an attempt to pinpoint impairment by identifying multi-level inconsistencies with normal functioning to provide an overview of the functioning of the auditory system in reaction to sound. Within this approach, the pure tone test remains the cornerstone of diagnostic audiometry but relies heavily on other measures tapping into different levels of the hierarchy to clarify its meaning. The reliance

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is dictated by the need for crosschecking, which states that no result is acceptable unless confirmed by an independent measure (Jerger & Hayes, 1976). The strongest crosscheck is provided by a measure that requires no voluntary response from the patient.

Some of these procedures are not hearing tests *per se*, but provide site-of-lesion information even though hearing sensitivity cannot be predicted from them. An example of such a measurement at a lower hierarchical level is immittance, being an objective measure of middle ear tympanic membrane movement with the variation of air pressure, while reflex testing determines the lowest intensity at which a stapedius reflex can be elicited (Block & Wiley, 1994; Katz, 1994). Together, they assist in the confirmation of a middle ear condition, provide information to distinguish between cochlear and retrocochlear pathology, may aid in the identification of patients at risk for retrocochlear lesions, and also help to confirm the presence of a non-organic hearing loss in cases of inconsistent 'severe' hearing losses (Margolis & Hunter, 2000).

Higher in the auditory mechanism hierarchy, the application of possibly the most valuable current tools to assist in the prediction of hearing sensitivity, for both screening and diagnostic purposes, can be found, namely, the oto-acoustic emission (OAE). Oto-acoustic emissions are low intensity acoustic signals that are generated by the outer hair cells of the cochlea in the organ of Corti on the basilary membrane spontaneously or in response to an acoustic stimulus (Kemp, 1979; De Waal, 2000). They reflect processes necessary in the cochlea for hearing to occur even though they are themselves not critical to the hearing process (Norton, 1993). Spontaneous oto-acoustic emissions have little clinical value, while the stimulus related oto-acoustic emissions (transient evoked, and distortion product) have made tremendous strides in the detection of hearing loss

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(transient) and the provision of frequency specific cochlear information (distortion product) in the two decades since its discovery.

The diagnostic use of the OAE is hampered by two limitations. The first is its inability to accommodate all degrees of hearing loss (Hall, 2000). Its application as a crosscheck is restricted to the moderate range of deafness. Thus, while a normal OAE possibly indicates normal outer hair cell functioning, an absent OAE does not provide adequate diagnostic information, requiring a crosscheck within the test protocol. The second related limitation is its high susceptibility to middle ear disease. The presence of middle ear pathology obliterates the OAE (Hall, 2000), also restricting differential diagnostic procedures that are especially important in the pediatric difficult-to-test population.

Probably the most valuable tool in the difficult-to-test battery that proved to be sensitive to various constellations of symptoms across the hierarchy of the ear is auditory evoked potentials[1] that are neural in origin. As in the case of pre-neural testing, evoked potential audiometry is a form of objective testing, and no voluntary response that an auditory stimulus was received is required. It deals with the extraction of small electrical amplitudes of the auditory system (eighth cranial nerve and higher) from larger EEG activity via surface electrodes on the scalp using complex computerized signal averaging techniques. Although it is not a test of hearing *per se*, AEPs provide information on auditory pathway integrity at various levels, albeit not in its entirety (De Waal, 2000).
AEPs are considered to provide the most reliable information on hearing sensitivity in the absence of definitive, reliable behavioral results (Hannley, 1986; Stapells, 1994; Hall &

[1] The application of auditory evoked potentials as a tool in the prediction of hearing thresholds and not applications with a neuro-diagnostic emphasis (such as intra-operative monitoring and detection of tumours) will be addressed.

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Bachman, 1998; Hood, 1998, Goldstein & Aldrich, 1999, Stapells & So, 1999). They are able to accommodate the full range of deafness, and the presence of conductive pathology may be clearly distinguished from sensory neural pathology (Hall, 1992; Hood, 1998). The remainder of the chapter focuses on evoked potentials elicited within the auditory system as an objective method of obtaining estimates of hearing acuity.

The additional value of evoked potentials compared to immittance measurements and OAE in audiometric procedures can be highlighted when measured against three related but independent parameters of corroboration, substantiation and delineation, as tabulated in Table 2.1.

Table 2.1 The benefits of evoked potentials using three parameters

	Test battery		
	Procedures not requiring voluntary responses from the patient		
	Crosscheck Continuum		
Procedure	**Corroboration** *Diagnostic information, beyond what may be obtained with a pure tone audiogram, may also be extracted to serve as confirmation or rejection of conclusions gathered from other testing procedures.*	**Substantiation** *It may also serve a supplementary role to the pure tone results with some patients.*	**Delineation** *The use of evoked potentials is indicated and justified in some patients as the only procedure to confidently quantify hearing sensitivity (Hall, 1992; Goldstein & Aldrich, 1999).*
Immittance	Able	Able	Unable to single-handedly provide information on hearing sensitivity.
Oto-Acoustic emission	Able	Able	Unable to single-handedly provide information on hearing sensitivity.
Evoked Potentials of neural origin	Able	Able	Able

Evoked potentials are able to meet all three criteria across the spectrum of nature (conductive versus sensorineural), degree (normal to profoundly impaired) and configuration of deafness (high versus mid and low frequency emphasis) within the test

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battery approach. An overview of the clinical utility (current practices, limitations and possible solutions) of evoked potentials in the assessment of difficult-to-test populations will hence be rendered.

2.3 THE CURRENT STATUS OF EVOKED POTENTIALS

2.3.1 Evolution of the field: from EEG to AEP

The EEG still remains the basis of any evoked potential measurement. Berger (1929) first recorded bio-electric activity, generated by the central nervous system without sensory stimulus. Based on this activity, it was discovered that these random bio-electrical events undergo stimulus related changes that may be extracted from the background EEG pattern called evoked potentials. Loomis (1938) documented a triphasic response to sensory stimulation in sleeping and awake patients and he named it the K complex. Based on his work, Davis (1939) and Davis et al. (1939) documented the presence of the K complex when elicited with auditory stimuli in sleeping and awake patients. The lack of sophistication in electronics, however, hampered exponential development because the stimulus related changes in the EEG patterns, based on auditory stimulus, were minuscule and often masked by the background EEG.

It was not until the invention of signal averaging techniques and the summating computer, enabling the extraction of low level evoked potentials from EEG, that evoked potential techniques became more documented in the field of audiology (Clark, 1958; Clark et al., 1961). The ability to convert and store analog data in a digital format revolutionised the detection of evoked potentials from the underlying EEG pattern.
As the changes in EEG resulting from fixed and synchronized stimulus remain consistent and the EEG random, the algebraic sum of repetitive consistent signals grows in proportion to the number of summed signals. The amplitude of the random noise of the

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EEG averages to zero. The magnitude of the evoked potential will, therefore, be enhanced, while the EEG is reduced to zero (Ferraro & Durrant, 1994; Goldstein & Aldrich, 1999). This principle is applied in the estimation of threshold using AEPs in two ways in particular.

Firstly, the changes in ongoing EEG activity may exhibit common, distinctive characteristics when auditory signals are presented at a certain intensity level. When these recordings at a particular intensity level are superimposed, traces may show replicability and are, therefore, at supra-threshold levels. When auditory signals are presented at successively weaker intensity levels, as in threshold audiometry, the traces, at some point, are no longer replicable and discernable from the EEG pattern. It may be inferred that an electrophysiological threshold has been reached.

Secondly, changes in latency (measurement in time pertaining to when a response occurs following stimulus onset) and amplitude (size of response) as a function of reduction in stimulus intensity are used in the estimation of threshold. Test signals and other stimulus and recording variables may influence the latency and amplitude of a response to an extent. It can, however, be assumed that a systematic increase in latency and decrease in response amplitude will occur when the signals become weaker, until the amplitude of the response is no longer detectable from the EEG background at an expected point in the time domain (latency). Again, an electrophysiological threshold may be inferred.

Following the advent of the signal-averaging computer in the 1960s, early interest in evoked potential audiometry was focused on the potentials that were of cortical origin, usually occurring 50 to 500 msec after stimulus onset. To a lesser extent but more or

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less at the same time, interest was developing in the potentials occurring at 10-15 msec. It was not until the first benchmark descriptions of the discovery of the Auditory Brainstem Response by Sohmer & Feinmesser (1967) and Jewett (1970) and Jewett & Williston (1971) however, that interest in AEP hearing estimation became more of a clinical reality.

It would not be an overstatement to declare that those historic reports on ABR revolutionized the field of diagnostics in difficult-to-test populations. Answers instead of speculation about the severity and nature of the hearing loss could be provided. The excitement may be summarized by Chiappa & Young (1985:76): *"EP's quantify and objectify data that the clinician may sense, EP's may localize lesions within a long sensory pathway, and EP's may be more 'efficient' and 'cost-effective' because the time consuming testing itself is usually done by paramedical personnel"*. The latter part of this quotation opens up many debates, which are beyond the scope of this paper. Despite the lack of insight into the critical role of audiologists in the diagnostic field, the comments on the role of EPs cannot be disputed, even though this report was published before the clinical induction of frequency specific tone burst stimuli into the protocols. So while the involvement of frequencies remained uncertain using click stimuli, previously undetected pathology could be identified and managed in a much more efficient way than before.

Current practice regards the ABR with its various protocols to be the procedure of choice to determine hearing ability. Nature, degree and configuration of hearing loss (Hood, 1998) can be identified, while normal ability may be ruled out. It provides sufficient site-of-lesion information to incur further referrals and, most importantly, an audiologist is able on the basis of ABR findings, to successfully select and fit amplification for any of

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the difficult-to-test clientele and commence with further habilitative or rehabilitative measures.

The challenges in the current clinical domain are, however, numerous and encompass such fundamentals as poor technical knowledge, weak interpretation by clinicians and poor control mechanisms (Kimura, 1985). Too often, the test sequences are performed without due acknowledgement of the rigorous criteria required of diagnostic test procedures. In fact, sub-standard techniques may be selected in active clinical settings for cost-cutting purposes. Some fundamental concerns have, therefore, lingered and some questions remain unanswered. Kimura (1985:79) continues to voice concerns in stating that the *"concepts of EP are not new, but recent evolution of the technique and its popularity, together with its profitability, are forcing many clinicians to perform the test without proper training or experience".*

The comments made by Kimura over 15 years ago still seem valid and applicable to current practice. His attack on the ethics and knowledge of professionals in the field ring true in many cases, but unfortunately his words seem to address symptoms but remain silent on the possible causes of this state of affairs. One possible cause of the lack of cohesion between research and clinical practice alludes to the inconsistency in the terminology and classification systems of AEPs.

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2.3.2 Difficulty with classification

Despite the dramatic developments over the last 40 years, resulting in refined techniques and interdisciplinary expansions, the indiscriminate classification and terminology employed in the description of these potentials in a standardized form has not resulted from its frequent use in many a clinical domain. Most discussions on the categorization and terminology can best be summarized in three words: *non-standardized, misleading* and therefore *confusing*. As Ferraro and Durrant state: *"the standardization of the terms, abbreviations, and acronyms used to reference specific Auditory Evoked Potentials is woefully lacking, as is the general consensus regarding which to use, or which are the most descriptive of the response measured"*(1994:322). Ever since the technical capability to record evoked potentials in response to an acoustic signal became possible in the 1960s, their classification has been influenced by specialists in the field of hearing, neurology and otolaryngology, each providing their own perspective and terminological bias.

Consequently, inaccurate and confusing terminology has prohibited interdisciplinary cohesion in the application of auditory evoked potentials. The four most commonly used classification systems will be reviewed.

2.3.2.1 Classification in the time domain

The time after stimulus onset is known as the latency epoch, and, according to this classification, auditory evoked potentials may either be classified as short, middle or late latency responses. Short latency responses occur within 10-15 msec after stimulus onset. The components of EcochG, Auditory Brainstem Response, slow Negative potential and the frequency following response, or Steady State Evoked Potential are all

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short latency potentials (Moushegian, 1973; Davis and Hirsch, 1979; Ferraro & Durrant, 1994; Hall & Mueller, 1997).

Middle latency responses occur between 10-50 msec after stimulus onset. The 40 Hz responses are the most typical of middle latency responses. Late Latency responses occur between 50-500 msec after stimulus onset. The N1-P2 complex and the P300 are popular examples of late latency responses.

Within the time domain, none of the demarcated latencies has similar nonclomenture. The waveforms of the ABR are delineated with Roman numerals I to VII, while the EcochG potentials are described by what they represent- cochlear microphone, action potential and summating potential. In middle latency epochs, responses are described according to polarity: P equals positive and N equals negative with alphabetical subscripts with one exception (a zero preceding the negative peaks: N0 (zero) followed by Na, Nb). The P300, a late latency response, is categorized according to its absolute latency in other words, the time after stimulus onset. It is also known as the P3, based on morphology – the third positive peak of the late latency responses.

It would be stating the obvious to declare that the time classification is non-standardized, yet it is most often used in the general description of AEPs. More importantly, its use is strictly speaking highly inaccurate. Most of the classification occurs *after* the latency epoch has been determined, in other words, the time domain is rarely used. The only exception is the P300, which utilizes the time domain in the identification of the actual component. In the case of short latency epochs, the use of, for example, Wave V, or Cochlear Microphonic is employed. In the pure sense, these terms do not refer to the time domain.

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2.3.2.2 *Classification based on anatomic origin*

"*Precise origins of all AEP except Wave I of the ABR (EcochG N1) is still a controversial area*" (Ferraro & Durrant, 1994:320). Of the four classification methods, anatomic origin is the most misleading. Differentiation is based on the site in the auditory system where the bulk of the response is generated. Although this definition is vague enough to accommodate neural interaction, it has created a false sense of accuracy, implying that these anatomic origins have somehow been clearly identified. It, furthermore, dismisses the complexities of the neural system such as the interactions between sensory modalities, the sensory and motor interface, and autonomic-, voluntary and interhemispheric communication (Goldstein & Aldrich, 1999).

Each latency epoch is reflective of an arbitrary level of the auditory system: SLRs are generated in the auditory periphery up to midbrain level brainstem. MLRs are generated in the area between the inferior colliculus and the primary auditory cortex, and LLRs are cortically generated. The link between sites of generation is tenuous, as all AEPs except for EcochG measurements generally utilize scalp recording techniques, isolated from the electricity that occurs at cellular level.

The biggest misnomer, and unfortunately the most widely used, is the ABR. For instance, the first two components of the auditory brainstem response arise from the auditory nerve. The wide application value of the ABR has, furthermore, resulted in AEPs being described as 'brainstem responses', irrespective of the latency epoch, and that equipment that is able to record AEPs is considered 'brainstem machines' (Goldstein & Aldrich, 1999). Not only is the term in its allocated place misleading, but its use as an umbrella term for AEP is grossly inaccurate.

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2.3.2.3 Classification based on the stimulus-response relationship

Two subcategories exist in the stimulus –response relationship: responses may be described as either *transient* or *sustained*, or, they may be described as *exogenous* or *endogenous* (Ferraro & Durrant, 1994). Transient evoked responses have fast rise/fall times because the response is dependent on rapid changes in stimulus. AEPs elicited with clicks and short tone bursts are transient for instance the ABR. Sustained AEPs indicate that a sustained response (lasting as long as the stimulus) is elicited. The cochlear microphonic and summating potentials of the EcochG are examples of sustained potentials (Ferraro & Durrant, 1994).

Exogenous waveforms depend on the physical form of the stimulus. All short and middle latency responses, as well as the N1and P2 of the LLRs are exogenous. Endogenous waveforms such as the P300 are perceptual in nature, and the response is largely independent of the physical features of the stimulus. Context sensitivity exists which entails the ability to recognize and/or attach meaning to the stimulus (Hall, 1992; Ferraro & Durrant, 1994;Wilson, 2000).

The difficulty with this classification system resides in its unbalanced application. The term *exogenous* is rarely used to identify the OAE, the ABR or any of the middle latency response components. The inverse term of *endogenous* is, however, frequently used but not within the classification continuum it was developed from. It is employed independently as a descriptive term to subtly allude to patient participation in evoked potential procedures, usually at supra-threshold level such as the P300, or as a synonym for some of the cortical late latency responses, thus adding to the existing confusion.

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2.3.2.4 *Classification according to the location of the recording electrodes*

Near field recordings entail the placement of electrodes near or on the response generator, and it is indicated when placement has a profound effect on the waveform morphology. Far field recordings consider electrode placement to be a less critical variable (Ferraro & Durrant, 1994). In evoked potential procedures, this type of classification serves little purpose as all recordings are considered far field, except for two very specific instances, namely, the trans-tympanic placement of the EcochG TipTrode and the intra-operative direct monitoring of the nerve in very specific cases. It could be argued that direct nerve monitoring could be related to near field recordings, but the invasive nature of the procedure and the medical support it requires prohibits its routine application by audiologists, rendering this type of classification less useful.

2.3.3 Terminology used for Auditory Evoked Potentials

No discussion on the non-standardized classification of AEP would be complete without noting that some of the AEPs are known by various names. Hall (1992:16) states that *"inconsistencies in terminology abound in the literature"* and that these inconsistencies contribute to errors in clinical situations. For instance, 'auditory brainstem response', 'brainstem auditory evoked potential', 'brainstem auditory evoked response' and 'auditory brainstem evoked response' all refer to the same thing. Ferraro and Durrant (1994) note no fewer than 10 names for the ABR. The name issue would not be as confusing if it were only a difference in word order that separated the disciplines describing AEPs. What hinders clarity, however, is that more often than not, initials or acronyms only refer to the response. This results in reports containing results of BAEP or BAER measurements, sans clarification.

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In summary, the time domain classification does not relate to the time domain, and the anatomic classification rarely places the sites of origin accurately. The stimulus-response relationship is used in an unbalanced manner, while the classification based on electrodes is redundant due to an extremely limited occurrence of near field recordings in clinical audiology. Current practice follows a mixture of all classification systems, primarily using latency and anatomic terms. The AEPs concerned with threshold estimation will be reviewed in this study using latency and anatomy as classification references.

The purpose of the preceding discussion may be summed up by Georg von Békesy (1960:7) who stated that *"one of the most important features of scientific research is the detection of errors. The writer believes that positive results and failures ought to be discussed together. Only by such complete reporting can we get a true conception of a piece of work, of the manner of its development, and of the limitations of its principles"*. While the *positive results* of increased accuracy in the identification of hearing loss are merited, the users of evoked potentials and the pioneers in the field have *failed* by not addressing the need for a uniform and clear classification system. This *limitation* should be addressed in order to lessen confusion and simplify descriptions across disciplines. A current solution is unavailable at present, however. The origin of the terminological maize the field occupies may best be summarized by the sobering words of Kimura (1985:79) when he stated that: *"Abuse and misuse are common with any new diagnostic procedures. The problem, however, is particularly acute in* ***EP studies that have become routine before their time, while the technique is still evolving rapidly****"* (emphasis mine).

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Even though the discussion of terminology and classification is somewhat disheartening, the testing procedures themselves have gone from strength to strength. Perhaps the most important objective at this juncture, therefore, is to bring all clinicians to a uniformly high level of clinical competence (Hall & Mueller, 1997). The specific modifications and adjustments available to accurately predict hearing using evoked potential measures will now be reported and evaluated within the context of difficult-to-test populations.

2.4 TOWARDS OPTIMAL OBJECTIVITY WITH FREQUENCY SPECIFICITY: USING AUDITORY EVOKED POTENTIALS IN THRESHOLD PREDICTION

It has been established that in order to obtain threshold estimates of hearing, certain wave patterns and configurations are elicited by manipulating the equipment, the signal and even the subject during AEP procedures (Hall, 1992; Hood, 1998; Goldstein & Aldrich, 1999). The specific clinical purpose of evoked potential procedures will, therefore, dictate every selection of variable that may be controlled.

Two questions are identified that may govern the appropriate selection of evoked potential parameters. The first and most obvious is whether an *"ABR [can] accurately predict the pure tone audiogram in the clinical population"* (Oates & Stapells, 1998:61). A similar question was posed by Picton (1991). Stated differently by Goldstein & Aldrich, *what would this patient's threshold audiogram have been had I been able to obtain it reliably by behavioural response audiometry (1999:110).* Eggermont (1991) makes a further addition when he states that the question should enquire into the conditions under which evoked potential measurements could have been expected in threshold estimation.

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The question posed by Goldstein & Aldrich (1999) subtly guides the researcher to closer examination of two separate but related criteria that need to be addressed when using evoked potential measurements for threshold estimation in difficult-to-test populations. The first is the necessity for objectivity in testing endeavors, while the second pertains to the requirement for frequency specific data. Unfortunately, most of the more traditional AEPs cannot single handedly provide objective frequency specific information. From the outset, therefore, a test protocol and the inclusion of a number of AEP measurements are implied, in an attempt to provide frequency specific indices of threshold without sacrificing objectivity. When used and interpreted properly, AEPs may provide the diagnostic audiologist with reliable estimates of auditory sensitivity where pure tone results are rendered inconclusive (Hood, 1998). According to Oates & Stapells (1998) the test protocol should at least include tonal stimuli ABR measurements. Their findings indicate that ABRs to be elicited by tonal stimuli presented with notched noise predicted reasonably accurately in the range of 0.5 - 4 kHz thresholds, previously unavailable with unmasked clicks. While the limitations of click ABRs are well documented, Gorga (1999) justifies their clinical use in threshold seeking protocols by the high frequency data they provide in the critical 2-4 kHz regions. For this reason, and possibly due to their relatively clear wave morphology, they remain the most widely used in AEP procedures (Picton, 1991; Hood, 1998; Hall, 2001). Bone conduction protocols in AEP may also be employed to clarify the nature of the hearing loss as being conductive or sensory neural (Hall, 1992; Hall & Mueller, 1997; Hood, 1998; Oates & Stapells, 1998).

Eggermont's (1991) question on the ideal conditions for evoked potential measurements indicate, additional to the above, dependency on subject state, the stimulus to elicit the recording, as well as some form of masking to ensure place and frequency specificity. The experience of the tester also becomes an additional consideration. These issues

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and techniques will be presented in the following section by addressing their contributions to the objectivity and frequency specificity of AEP for threshold prediction, with specific focus on Auditory Brainstem Response Testing.

2.4.1 Elusive objectivity of Auditory Evoked Potential recordings

Cope (1995) defines objective audiometric testing such as AEPs as testing procedures that require no voluntary response that an auditory stimulus was perceived. However, it is scientifically incorrect to assume that an involuntary audiometric response does not imply that the test results are objective. True objectivity is hindered in most evoked potential audiometric procedures by the introduction of human perception into the data analysis process. The level of expertise required to judge the presence of responses accurately at threshold level causes a myriad of complications that affect the reliability, validity and ease of recording for both patient and professional in multiple ways, depending on the test situation as a whole.

Another concern arising from the subjective analysis is the false sense of security created by the use of numerical entities, for example, to describe results. A statement by the British scientist Tooth in the 1940s is very applicable to AEP measurement: "*Where knowledge of a medical condition is incomplete, there is a danger that the results of ancillary aids, especially when expressed in numerical terms, may acquire an unwarranted appearance of infallibility*" (Tooth, 1947:469). While the subjective interpretation of results form the biggest hindrance towards objectivity, the limited use of technology, as well as subject influence also need to be addressed.

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2.4.1.1 Technical influences

Kimura (1985) warned clinicians of the abuses and misuses of the ABR when he criticized the lack of technical knowledge evident in practice. Developments in test stimuli and techniques in evoked potential audiometry has enabled researchers, more than clinicians, to provide accurate estimates of hearing sensitivity using mostly ABR measurements. Masking and filtering techniques are regularly refined and updated by researchers, but availability and application for clinicians remain limited. For instance, the technical support for waveform manipulation and access to the software to enable the generation of sophisticated stimuli are not clearly evident in practice (Balfour et al., 1998). Despite the obvious benefits created by techniques that enable frequency specific hearing estimates, their cost and complex theoretical orientations cause restricted access. This situation has been sharply criticized by Gorga (1999), who believes that difficulty and cost should not hamper the correct use of any audiometric measure.

2.4.1.2 Subject influences

The subject may induce inaccurate recordings through interference with the recording situation. Sedation is often administered to ensure low noise levels. The use of sedation is not without serious ethical and medical implications, and a multitude of measures need to be in place before a patient is sedated (for example, informing parents of the necessity and possible complications and ongoing, accessible medical support). Body movement, tenseness and inability to follow test instructions to remain quiet register excessive noise levels on equipment that have an adverse effect on the reliability of the recording (Wilson, 2000).

EP recordings are also considered time consuming, and initial noise levels may be elevated after a certain amount of time has lapsed. A practical example would be the

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sedated patient waking up before the test has been completed, forcing clinicians to either re-schedule or rely on incomprehensive results. The absence of appropriate, clinic-specific control values for comparison, furthermore, causes arbitrary judgement of auditory function. It forces clinicians to rely heavily on information from other tests, disregarding the reason for EP referral in the first place, namely the questionable reliability of the preceding tests (Hyde, 1991).

2.4.1.3 *Expertise of the professional*

Possibly the factor that causes the most concern is the high levels of expertise needed to accurately interpret results at threshold level as Goldstein and Aldrich (1999:110) rightly conclude: "*Subjectivity of human observers adds large variance to the threshold estimations*". At threshold level, the wave morphology deteriorates, while the amplitude of the waveform decreases (Hood, 1998). Threshold is reached when a peak of a waveform can no longer be detected from the background EEG activity. Although the recording may, therefore, be objective, subjectivity is transferred to the clinician interpreting the test results. Wilson (2000) suggests a rating scale and a three-subject inter rating procedure to ensure accurate estimates of hearing levels during ABR testing. While that may be the ideal, the suggestion is time consuming and often impractical, if not impossible.

This whole argument has been aptly summarized by Hyde who states that: "*It is often assumed, especially by those with little or no hands on experience with AEP testing, that an ABR is an ABR is an ABR. This is not so. There are good and bad test conditions, good and bad instrumentation, good and bad tactics, and good and bad interpretations. There is a tendency to overlook this problem partly because of the illusion that AEP test results are objective. In reality, subjective judgment intrudes in many facets of AEP*

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testing. There are some testers who achieve almost magical accuracy in threshold estimation, for example, but there are others for whom no amount of training is sufficient. Thus, it may be desirable for those who acquire AEP testing services to shop around, and it is also desirable to try and verify whether anticipated test accuracy is actually being achieved. These points apply, of course, to many other non-trivial non-AEP procedures" (1991:26).

2.5 THE 'PERFECT' AUDITORY EVOKED POTENTIAL AND THE TECHNIQUES AND DEVELOPMENTS TO ATTAIN FREQUENCY SPECIFICITY

2.5.1 What is a 'perfect' Auditory Evoked Potential?

The first and foremost goal in threshold estimation is, of course, **to obtain an audiogram that indicates threshold levels across the frequency spectrum**. If it is impossible to extend the information across the entire pure tone frequency range, the frequency area between 0.5 and 4 kHz should at least be targeted (Sohmer & Kinarti, 1984). To attain this goal, certain criteria have to be met by the evoked potential procedures that will be enlisted for the task. Each of the criteria will be listed and the current techniques explored in terms of how they specifically rise to the occasion. The most important of these are the following:

Criterion 1:

The AEP should provide a reasonably accurate assessment of threshold (Picton, 1991)

In the quiet, awake adult almost any technique from the arsenal could be successfully employed for the task (Stapells, 1984). In *ideal* testing conditions, the early, middle and late responses may be recorded near threshold level. The ABR Wave V has been detected within 10dB of the pure tone thresholds (Elberling & Don, 1987). Pa of the

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MLRs and N1 of the LLRs are typically within 10 to 20 dB of threshold (Picton, 1991). In typical recording conditions, responses were elevated to 20dB above threshold for short latencies and later waves top approximately 30 dB above threshold (Picton, 1991).

Criterion 2:

Changes in subject arousal should not affect the recording of an AEP (Picton, 1991)

The stage of wakefulness and the influence of sedation dramatically influence the presence of certain waveforms from the background EEG activity, as background EEG noise is higher during sleep (Picton, 1991; Hall, 1992; Hood, 1998). Although some waveforms increase in amplitude during sleep, for example, the P2 and N2 of the LLR, most evoked potentials decrease during such a situation. The early potentials such as the ABR are quite stable during changes in arousal and anesthesia, but the middle latency waveforms become delayed and distorted during sedation (Thornton et al., 1984). Late potentials may exhibit more difficulty in recognition as, in an attempt to compensate for poorer signal-to-noise ratios, averaging is increased over different stages of sleep, distorting and attenuating responses. In general, Picton (1991) usually found late responses to be absent.

Criterion 3:

AEP recognition should not be influenced by age (Picton, 1991)

The Late Latency Response (LLR) is sensitive to aging and to stages of sleep, making it difficult to compare across age groups (Kurtzberg, 1989). The Middle Latency Responses (MLR) are not clearly recognizable in children under 10 (Kraus et al., 1985). The additional influence of state of arousal further complicates their application: MLRs are more easily recorded in wakefulness and Stage I sleep, variable in Stage II and III

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sleep, and poorly detected in Stage IV sleep. The 40 Hz responses also show poor validity in infants and cannot be reliably recorded in this population (Stapells et al., 1988).

The electrocochleogram and the auditory brainstem response show recognition at all ages, despite developmental changes in the first 18 months of life for the ABR (Hecox & Galambos, 1974). Aging effects were also identified by Allison, Wood & Goff (1983), but presently ABR can currently be recorded in all age groups, with maturity and stability between 10-60 years of age (Hood, 1998).

Criterion 4:

The responses should be present at all frequencies of the pure tone audiogram (Picton, 1991)

Although this criterion has much to do with the type of stimulus, it seems that in general, the middle and late latency responses show good estimations of low frequency thresholds in awake adults and older children (Galambos, Makeig & Talmachoff, 1981; Picton, 1991). The 40Hz responses are still preferred in the estimation of low frequencies (Hood, 1998) and suggested by others (Hall, 1992). Traditionally, the ABR with click and the ECochG are associated with high frequency hearing. Recently, frequency specific techniques have been introduced with more regularity, and these will be explored within the context provided by the next criterion.

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Criterion 5:

The perfect AEP should measure response levels that are specific to different frequencies on the audiogram (Picton, 1991)

The biggest obstacle in this regard is not the response itself but the stimulus employed to elicit the response (Picton, 1991). A broadband click is not frequency specific as the stimulus activates across broad frequency regions. Two additional techniques have been employed to obtain more frequency specificity with brief stimuli. One is directed to the stimulus component, while the other focuses on spectral enveloping and masking to prevent overspill of the response into neighboring frequency regions. The stimuli options, envelopes and masking options will hence be discussed.

2.5.2 Stimulus effects on the use of Auditory Evoked Potentials in threshold prediction

2.5.2.1 Click stimuli

Click stimuli are described on the basis of how they are perceived audibly. They are short (0.1 msec), broadband stimuli, which activate a large number of neurons simultaneously based on the acoustic principle of the shorter the stimulus duration, the broader the frequency content. As these neural responses can be presented at various intensity levels during evoked potential measurements, responses may be related to hearing thresholds. The shorter the stimulus onset, the better the neural synchrony and the worse the frequency specificity. Accurate information at different frequencies can, therefore, not be obtained (Picton, 1991; Hall, 1992; Hood, 1998; Gorga, 1999).

Despite its broadband nature, responses on clicks show most agreement with pure tone thresholds at 2000–4000 Hz, with lesser correlation at 1000 and 8000Hz and no accurate information about sensitivity at lower frequency regions (Oates & Stapells,

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1998; Hood, 1998). The correlation with high frequency pure tones is mostly created by the frequency response of the earphones - clicks approximate the frequency response curve of the transducer, although the tonotopical arrangement of the hair cells in the cochlea also contributes to this response (Rance et al., 1998; Oates and Stapells, 1998; Gorga, 1999).

The value of click ABR in the examination of eighth nerve and auditory brainstem pathway integrity is undisputed (Picton, 1991). The information obtained can assist in ruling out the possibility of neural involvement in cases where neurological deficits are uncertain. As a matter of fact, the use of click ABR as stimulus has made audiology as much related to neurology as to otolaryngology (Starr, 1998). The clear wave morphology, well defined waveforms, and limited susceptibility to electrical artifact has ensured that click-evoked ABR forms an integral part of neurological evoked potential batteries: detection of acoustic neuromas, silent plaques of multiple sclerosis and other brainstem lesions have included click ABR (Hecox & Galambos, 1974; Starr, 1977; Selters & Brackman, 1977; Chiappa, 1984). Clinical research on myelinization, the presence of tumours, effects of stroke and neural infections in the auditory pathway have included click ABR in the respective test batteries (Halliday, 1993). From a neurological point of view, Starr (1998) states that click ABR provides differential diagnosis in subgroups of hearing disability that involve to some extent a disorder of the auditory nerve. He correctly claims that sensory involvement can be differentiated from neural involvement and that the relative contributions of the two processes may be distinguished. He concludes that awareness of the role of the auditory nerve in hearing function may lead to development of new ways to treat deficits in hearing.

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Despite this differential diagnostic argument, controversy still exists, from an audiological perspective, regarding the usefulness of click-evoked ABR in hearing threshold estimation. Oates & Stapells (1998) discredit the validity of click-evoked responses at 2000-4000Hz for threshold estimation and conclude that the information it provides does not translate accurately into hearing thresholds for individual patients. Click-evoked responses, moreover, do not provide information on the degree of hearing loss.

Some researchers still include click ABR as part of a threshold test battery. Gorga (1999) states that information from a click-evoked ABR is still useful for high frequency threshold estimation, although he concedes that low frequency information (lacking when conducting a click ABR) is essential in the selection of hearing aid response characteristics. Hood (1998) includes click ABR as the first component in her evoked potential test battery yet warns: *"click information is not sufficient to understand auditory function across the frequency range or to appropriately fit amplification"* (p.108).

It can be concluded that, although click-evoked ABR results should be interpreted with caution, they provide ample diagnostic information to justify inclusion in threshold estimation. They provide a general estimation of high frequency hearing that may assist in further delineation of diagnostic considerations.

When hearing loss is present, it typically involves at least the higher frequency regions. Habilitative options are larger for high frequency hearing loss than some of the other configurations of hearing loss (Gorga, 1999). In fact, it is considered rare to find low frequency hearing loss with normal high frequency hearing. Cochlear mechanics place an absolute limit on the amount of low frequency sensory neural hearing loss that may be present with normal hearing function in the cochlear base. No more than a moderate

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to severe low frequency hearing loss is possible, when thresholds are within normal limits in the high frequencies, irrespective of the condition of the cochlear apex (Thornton & Abbas, 1980). Additional to providing some high frequency information to assist in hearing aid fitting, it also rules out the possibility of neurological involvement, a vital procedure when considering the increasing documentation of pathology such as auditory neuropathy and the relatively marked incidence of acoustic neuroma when compared to other brain tumors.

2.5.2.2 Tone burst stimuli

A trade-off occurs between frequency specificity and neural synchrony in the search for frequency specific stimuli. The difficulty resides in the fact that most evoked potentials are elicited by brief stimuli or, in some cases, by the onset of linger responses. This results in a physical limitation of the stimulus to be frequency specific, as a brief stimulus will have energy in regions outside of the signature frequency. Tone bursts are more frequency specific than clicks, but are still not as frequency specific as pure tones (Hood, 1998). Wave morphology elicited by tone bursts, especially the earlier waves, is compromised due to reduced neural synchrony.

Goldstein & Aldrich (1999) describe tone bursts as short duration stimuli with narrow spectra and some tonality, which render closer approximation of the pure tone thresholds than click stimuli. The largest concentration of acoustic energy occurs at one frequency and then spreads to surrounding frequencies. These narrow spectrum signals may, therefore, be used "*to obtain audiograms that more clearly resemble threshold audiograms obtained with conventional long duration tones in voluntary behavioural response audiometry*" (Goldstein & Aldrich, 1999:66).

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Oates & Stapells (1998) state that the use of tone burst ABR can provide a valuable tool for assessing peripheral hearing sensitivity in difficult-to-test populations, provided that the stimulus, noise masking and recording parameters are meticulously selected to ensure optimal frequency specificity. When the stimulus and recording parameters are carefully selected, the strongest side bands of energy are well below the level of the fundamental energy band, enabling the detection of frequency specific data. Even in low-level signals, the fundamental or dominant frequency clearly dominates the stimuli.

To decrease the spread of energy outside of the nominal frequency, special envelopes and gates for brief tones may be used that will concentrate the energy (Gorga, Abbas & Worthington, 1985). The envelope determines the relative amplitude between the main lobes of energy and the side lobes. The gating function determines the nature and the rate of onset (rise) and fall time as well as the plateau duration (Gorga, 1999).

The rise/fall time of the stimuli have a direct bearing on frequency specificity: the longer the rise and fall time, the better the frequency specificity with lesser occurrence of splatter of stimulus energy above and below the nominal frequency (Hall, 1992; Stapells, 1994; Stapells, Gravel & Martin, 1995; Hood, 1998). The length of the rise/fall time of the tone burst is, however, limited to no more than 5 msec, because longer duration causes the amplitude of Wave V of the ABR to decrease significantly (Stapells & Picton, 1981). The plateau has no influence on frequency specificity (Hood, 1998). The width of the energy lobes in the amplitude spectra, therefore, depends on the duration of the stimulus.

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2.5.3 Envelope effects on Auditory Evoked Potentials used for threshold estimation

Changes in the envelope affect the spectrum, physical intensity and loudness due to duration changes and temporal integration. While linear windowing function results in a 2? dB difference between the dominant frequency and the first side frequencies with a further decrease of 12 dB/octave in following side energy bands (Oates & Stapells, 1998; Gorga, 1999), it is not ideal. The abrupt changes from no stimulus, to the rise with additional sharp changes at plateau levels, are problematic, even though energy is concentrated around a center frequency, with reduced but present energy bands at adjacent and distant frequencies as well.

Blackman or Hanning (cosine squared) windowing are preferred to linear windowing (Hall, 1992; Hood, 1998; Oates and Stapells, 1998) because of the more gradual on- and offsets, resulting in less spectral spread of energy into other frequency ranges. For a Blackman gated tone burst, the first side lobe shows a 58 dB decrease in relative energy, which is considerably more than that achieved with a linear gating function. Adjacent energy bands decrease at a rate of 18 dB/octave after the first side band (Gorga, 1999; Goldstein & Aldrich, 1999).

Blackman thresholds tap into the auditory fibers responsible for a specific stimulus frequency and these nerve fibers that enervate the cochlear base, therefore have sharp tuning around this particular frequency (the frequency to which they are most sensitive). This does not mean that high intensity levels will not excite nearby frequency regions. Even low frequency pure tones, having an extremely narrow amplitude spectrum, will excite tails of fibers ennervating higher frequency regions once the level exceeds approximately 60 dB relative to the best threshold for these fibers. Blackman windows

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provide as much but no more frequency selectivity as, but no more than the normal cochlea itself (Gorga, 1999).

The preference of which filter to use remains mostly academic and research-orientated, as most of the manufactures pre-select Blackman ramping in their software prior to commercial distribution. It is, however, important for clinicians to be cognizant of the variables and software complexities available within the field of AEP and to fully appreciate their contribution to frequency specific threshold estimates.

2.5.4 Masking techniques in Auditory Evoked Potential protocols

2.5.4.1 High pass filters for derived responses

The derived response technique has been proposed by Don, Eggermont & Brackman (1979) to obtain frequency specific information from broadband stimuli. The broadband response, elicited by click, could be parceled into responses coming from more narrowly defined frequency bands (Teas et al. 1962). The procedure entails the progressive lowering of the cut-off frequency of a high pass filter and an ABR is then obtained at each of the cut-off frequencies. The thresholds of each recording at adjacent masker cut-off frequencies are subtracted from one another. High pass filtered noise is effective as it appears to desynchronize neural output in frequency regions of the masker noise (Goldstein & Aldrich, 1999; Gorga, 1999). The remaining response, therefore, represents neural activity in frequency regions below the noise of the cut-off frequency. This enables the separation of specific wave components while asserting control over frequency regions that are being assessed. From this derived response, an audiogram can be constructed which shows excellent agreement with pure tone thresholds (Gorga, 1999).

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The major disadvantage of this technique, according to Picton (1991), is that the noise levels will increase to relatively high levels to enable the masking of the click, to such an extent that noise induced hearing impairment becomes a clinical reality. Moreover, this procedure has not had success clinically as a large number of responses are needed to derive the eventual audiogram. Waveform manipulation is also required, following the recording to subtract and compute the derived response which is, therefore, rather time consuming. Another factor is that the comfort of the patient may be jeopardized, as the same transducer is used for the noise and the click stimuli, often at high intensities as already mentioned. Lastly, data storage may become cumbersome.

Another variation on high pass filtering techniques was proposed by Kileny (1981) when he used high pass filters with tone burst stimuli in an attempt to mask higher frequency regions while obtaining response activity from lower frequency regions of the cochlea. He found that high pass filters seem to be inappropriate for mid and high frequency tones. Underestimation of degree of hearing loss at high frequencies also occurred, and it seemed that high pass filters were more sensitive to contributions from low frequency regions.

The use of high pass filters is limited to somewhat dated research protocols with little recent clinical application. Furthermore, the availability of notched noise (described in Section 2.5.3.2) and the abundance of evidence of its efficiency at increasing frequency specificity have significantly reduced the utility of high pass filters.

2.5.4.2 Notched noise

Notched noise has been proposed as a possible solution to increase frequency specificity of brief tones (Stapells et al., 1985; Stapells, 1989; Picton, 1991) as it restricts

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the responsiveness of the cochlear partition to frequencies within the region of the notch when the notch is set at a specific frequency range (Hall, 1992; Hood, 1995; 1998; Goldstein & Aldrich, 1999). Notched noise is added to prevent other low, mid and high frequency energy from contributing to data elicited from the nominal frequency (Stapells, 1994; Stapells et al., 1995; Oates & Stapells, 1998; Gorga, 1999). Less noise is generated within the notch causing the nominal frequency, within the notch, to have increased frequency specificity. Adding notched noise is more important at high intensity levels, at low intensities, additional notched noise does not seem critical due to decreased spread of spectral energy (Stapells et al., 1985; Beattie, Thielen & Franzone, 1994; Hood, 1998). Although there is still spread of masking into the notch, especially from low frequency regions, reliable frequency specific estimates of thresholds may be obtained at 0.5, 1,2 and 4 kHz (Stapells & Picton, 1981; Stapells et al., 1985; Stapells at al., 1990; Picton, 1991; Stapells, 1994; Stapells et al., 1995).

Notched noise provides a more efficient alternative than high pass filtered noise as multiple recordings are substantially reduced and no subtraction of waveforms is necessary. Unfortunately, additional special equipment is required to filter the noise and the masked level for each recording is critical. The chief disadvantage is that the lower frequencies in the noise may become masked (Picton, 1991). In the presence of abnormal tuning curves in the impaired cochlea, they may not exhibit the normal sharp tip at the characteristic frequency. This can result in improper masking by notched noise when it is presented at intensities below the peak of the tone (Picton, 1991).

Similar results as for the notch may be obtained with white noise, although the amplitude may be smaller (Stapells, 1984). Broadband white noise requires less complex instrumentation and calibration in conjunction with tone bursts. With the notch absent,

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partial masking of the nominal frequency occurs (Oates & Stapells, 1998). Although able to have similar frequency specificity as notched noise, the response amplitude is markedly reduced (~33 % smaller than with notched noise), making waveform identification more difficult (Stapells et al., 1985; Stapells, 1994). Consequently, broadband white noise has had limited clinical utility outside research laboratories.

Accurate estimates of hearing thresholds can be obtained from 500-4000Hz for all age populations at intensity levels of 10-30 dB nHL at all four frequencies, whether in quiet or notch noise masking (Stapells et al. 1990; Stapells, 1994; Stapells et al., 1995). The literature shows the following correlation with pure tone audiometry:

- Tone burst ABR estimations of pure tone behavioural threshold show a >0.94 correlation
- Tone burst ABR at frequencies 0.5,1,2,4 kHz with notched noise show a regression slope close to 1.0 in the detection of hearing loss versus normal hearing (Stapells et al., 1995)
- Age does not seem to affect results
- Studies with tone burst threshold estimates with notched noise masking indicated that more than 90% of cases were within 20dB of the pure tone threshold
- Accuracy was better in cases with hearing loss for hearing loss than those with normal hearing sensitivity in older children and adults (Stapells et al., 1990) and
- The audiometric configuration does not affect accuracy.

Oates & Stapells (1998) conclude that audiologists may be confident in relying on ABR thresholds for air conducted brief tones to estimate hearing sensitivity between 0.5 and 4 kHz with reasonable accuracy in infants, young children and adults. Furthermore, at

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moderately high intensities, the frequency and place specificity is enhanced by notched noise.

The tone burst is, however; still not popular among clinicians despite its proven increased frequency specificity. The reasons for this can possibly be related to the expense of the necessary software upgrades, the installation of a second channel, and the prerequisite obtaining of normative data. Clinicians may also feel daunted by the complexity of gating functions and the continuous rise/fall time adjustments per frequency in addition to the usual concerns of evoked potential audiometry.

The efficiency in test time can also hamper regular introduction of tone burst ABR into practice. Results for each stimulus will take the same amount of time as for a click ABR. Tone bursts at two frequencies will take twice as long, and threshold estimates at four frequencies will take four times longer than a click ABR.

Finally, the deteriorated wave morphology can also cause increases in analysis time when compared to click ABR, especially at threshold level. The lower the frequency, the lesser distinct the earlier waves even at moderate intensities (Stapells & Picton, 1981).

2.6 CONCLUDING REMARKS ON EXISTING TECHNIQUES – MORE THAN A TEST BATTERY

Earlier in this chapter (Section 2.5.1), it was suggested that the pure tone audiogram of a patient should be regarded as the primary objective for the use of auditory evoked potentials. This implies that the effectiveness of a protocol should be evaluated in terms of its confidence in determining the loudness level at which sound is audible 50% of the

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time across the frequency range; in other words, the efficacy of the procedure in detecting threshold in high and low frequencies.

Perhaps the most important result of the use of such a benchmark is to gain awareness of the cause and extent of the deficiencies in protocols (Hyde, 1991). Although rigid protocols are appropriate for certain designated uses of AEP, such as screening, they should not be implemented across the board. An unyielding enforcement of a test protocol would not optimize the comprehensive assessment of hearing sensitivity. Inflexible recording protocols, irrespective of patient response or stimulus characteristics, do not recognize the influence of age and physiological noise levels as the primary considerations, rather than the frequency of the test stimulus. "*This cookbook approach is often ineffective in measuring hearing with the AEP*" (Herrman & Thornton, 1991:21). As Eggermont (1991) states all AEP methods, if applied at the state of the art, are equally good; in other words, the responses all exhibit the acceptable standard deviation of 10 dB in optimal testing conditions.

The appropriateness of the test protocol will of course be colored by the audiogram configuration and nature of the impairment and it is therefore not as unambiguous. However, the time restraint that clinicians face takes its toll, in that time consuming ABR and MLR studies with tone burst, clicks and high pass masking and its various combinations are set aside for the simple broadband click ABR screening procedure. Eggermont (1991) warns that this situation may result in sub-optimal assessment of hearing in difficult-to-test populations.

Hyde (1991) offers a valuable solution in suggesting that the answer lies in decision protocols that connect various test procedures in a consistent and structured manner.

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He disagrees with the general acceptance of the test battery approach by suggesting that explicit goals should be set for diagnostic and therapeutic protocols, a technique which he considers far superior to the "*popular informal idea of a test battery – which generally does not seem to inspire either quantification or accountability*" (Hyde, 1991:25).

Some suggestions for test protocol inclusion follow. One suggestion is to record an unmasked click ABR at a high intensity (70 dB) and then decrease to threshold level to obtain high frequency information regarding hearing sensitivity and neural synchrony. A tone burst ABR at 500Hz masked with notched noise at the high intensities should then be recorded to threshold level to obtain low frequency information (Hall, 1992; Hood, 1998; Arnold, 2000).

Hood (1998) furthermore suggests that, instead of a tone burst ABR, the 40Hz Middle Latency Response (Galambos et al., 1981) could be utilised in older patients to obtain low frequency information. It provides a faster alternative to tone burst ABR: fewer stimulus sweeps are necessary and responses may be obtained within seconds. Clinical use is limited due to maturational and sedation effects on the response, and optimal recording is only achieved in quiet, awake adults.

One could conclude that this protocol enables the effective determination of hearing estimates within 10-30 dB of the behavioural response for 500 Hz tone burst or the 40Hz response while providing non-specific high frequency information near threshold. Although wave morphology will be interpretable at quite low levels, a complete audiogram cannot be constructed using the data, but enough information may be obtained in an efficient manner to provide habilitation to the individual patient.

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Another suggestion could entail singular use of tone burst stimuli with notched noise at 0.5- 4 kHz to threshold level as proposed by Stapells (1994) and colleagues (Stapells et al., 1995; Oates & Stapells, 1998) and Gorga (1999), disregarding click ABR. An audiogram may be constructed at approximately 20-30 dB above threshold for four critical frequencies. The poor wave morphology, complexity of stimulus parameters and long test duration impact negatively on the effectiveness of this suggestion, however.

In summary it can be stated that AEPs offer a variety of procedures with no recipe-like 'best' test that is suitable for all objectives and circumstances. Ideally, the use of more than one AEP measure would be suggested, moving away from the pre-occupation with a single test procedure that is applied in an indiscriminate manner, resulting in an assessment protocol that is not in the patient's interest (Hyde, 1991). The selection of the protocol should also accommodate local variables like the prevalence of disorders and multi-study indicators of test and protocol performance. Professionals should have workable knowledge, and their training should be continuous within an environment where good equipment maintenance is considered of cardinal importance. Hyde (1991) suggests a rule of thumb that if clinicians perform AEPs less than once a week, they should not perform them at all.

2.7 NEW POSSIBILITY – A BRIEF INTRODUCTION TO THE STEADY STATE TECHNIQUE

A new technique, without some of the problems facing other frequency specific attempts in the AEP domain has recently emerged in clinical studies termed the **auditory steady state evoked potentials**. This phenomenon consists of the use of tones, modulated in amplitude at rates between 75-110 Hz, which seem to improve the *frequency specificity* of the stimuli. In addition, automatic detection is introduced, as the responses are

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detected within the frequency domain and as such seem to be the first example of *true objectivity* in threshold estimation. The technique is similar to ABR in time domain, with the same insusceptibility to age and arousal effects, but differs substantially in stimulus and recording techniques. Steady State Evoked Potentials will be discussed in Chapter 3 in terms of their developmental history, key concepts and nonclomenture, and similarities to and differences from existing behavioural and objective techniques, as well as their application value in difficult-to-test populations.

2.8 SUMMARY OF CHAPTER TWO

This chapter serves as an introduction to the challenge facing evoked potential audiometry, namely, to provide objective, yet frequency specific estimates of hearing acuity in populations where conventional behavioural results are inconclusive, inaccurate or unattainable. Termed difficult-to-test, these populations were described in terms of the causes for uncooperative behavior during conventional testing. The introduction of objective techniques was motivated with specific reference to auditory evoked potentials as the method of choice to estimate hearing thresholds. Within the domain of auditory evoked potentials, an overview of development and classification was provided. The characteristics of the 'perfect' AEP were listed and current techniques were assessed within this context. The chapter concludes with an introduction to the Steady State Evoked Potential as an improved alternative to existing documented techniques.

> ***'There are good and bad test conditions, good and bad instrumentation, good and bad tactics, and good and bad interpretations. There is a tendency to overlook this problem partly because of the illusion that AEP test results are objective. In reality, subjective judgment intrudes in many facets of AEP testing" (Hyde, 1991:26).***

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CHAPTER THREE
STEADY STATE AS A NOVEL AEP TECHNIQUE IN THE ESTIMATION OF HEARING

Aim of the Chapter

This Chapter will introduce the auditory steady state as an auditory evoked potential utilized in the prediction of hearing in difficult-to-test populations.

3.1 INTRODUCTION

In this chapter, the new AEP phenomenon of ASSEP will be explored. To provide a logical starting point for the characteristics of ASSEP, a definition will be rendered in terms of what it is (and is not) in relation to other AEPs. Following that, an outline of the signature characteristics of ASSEP will be highlighted. The underlying mechanism of the Auditory Steady State Evoked Potential will then be expounded, as it differs substantially from the mechanisms of existing AEP procedures. The influence of variables such as multiple stimuli, intensity, frequency and measurements within the frequency domain will be discussed.

It will become clear from the above discussion that the ASSEP poses a novel view on our traditional conceptualization in AEP procedures. Therefore, the discussion will logically continue with the application possibilities of ASSEP in the context of hearing estimation as a new tool in the electrophysiological arsenal of hearing tests. This discussion will expose the limitations of the ABR, as the most clinically used electrophysiological hearing estimator, while providing an overview of the clinical utility of ASSEP in recent research papers. The chapter concludes with an introduction to the

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purpose of the study created by the caveats evident in existing clinical research on ASSEP.[2]

3.2 TOWARDS A DEFINITION OF AUDITORY STEADY STATE EVOKED POTENTIALS[3]

In order to define what a steady state response is, a logical starting point is to define some of the characteristics in relation to other evoked potentials such as OAE and ABR. The stimulus (Section 3.2.1) and response (Section 3.2.2) characteristics will be discussed separately.

3.2.1 STIMULUS USED IN AUDITORY STEADY STATE EVOKED POTENTIALS

3.2.1.1 Transient versus sustained/continuous

The stimulus differs from those used in other evoked potential procedures such as OAE and ABR. Transient evoked OAE, for instance, and ABR stimuli are transient in nature. Buchwald & Huang (1975) describe a transient potential as one that is evoked when the auditory system is allowed sufficient inter-stimulus intervals to return completely or

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[2] Short abbreviation reminder:

ASSEP	Auditory Steady State Evoked Potential
MFASSEP	Multiple Frequency Auditory Steady State Evoked Potential
ABR	Auditory Brainstem Response
AM tone	Amplitude Modulated tone
FM	Frequency Modulation

[3] List of Terminology:

Modulation Frequency:	The rate of modulation which differs significantly depending on the application of the steady state response.
Carrier Frequency:	The low, mid or high frequency tone that is being examined of which the psycho-acoustic correlate is pitch.
Fundamental Frequency:	The same as the modulation frequency.
Fast Fourier Transform:	A method that is used to transform waveforms form the time domain (in milliseconds) to the frequency domain (in Hz). The FFT converts the data and the response is detected at the modulation frequency.

The tone at a specific carrier frequency is modulated at a specific, different frequency and through Fast Fourier transform the response is detected at the modulation frequency.

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mostly to its initial state before the next stimulus is presented. If the inter-stimulus time is shortened in such a way as to overlap, the compound potential that appears is called a steady state response (Regan, 1989) The potential is only generated in the rate of presentation is, therefore, only sufficient to cause an overlapping of these transient potentials (Kuwada, Batra & Maher, 1986) The tone is, in other words, ***continuous*** or ***sustained*** (Regan, 1989).

3.2.1.2. Modulated stimuli

The stimulus is ***modulated*** in amplitude and/or frequency at frequencies between 3 and 200 Hz (Figure 3.1). The sinusoidal amplitude modulation evokes the Steady State Response, which can be detected at the frequency of modulation (Kuwada et al., 1986; Chambers et al., 1986; Picton et al., 1987; Cohen et al., 1991; Dolphin & Mountain, 1993). For example, if a 1000Hz tone is modulated at 91Hz, the steady state evoked potential can be detected at 91Hz on the frequency axis (Figure 3.2). The sinusoidal modulation of the amplitude of a continuous tone, therefore, evokes the steady state response (Kuwada et al., 1986; Picton et al., 1987). Stated differently, without the modulation, no steady state response would be evident.

3.2.2 Evoked response

"*To most western minds, everyday experience seems to be a succession of transient events, each of which has a beginning and an ending. For example, a musical melody may contain several different tone frequencies, but each note lasts only for a brief time rather than enduring indefinitely. Thus, our everyday experience predisposes us to regard a time-domain description of physical events – including oscillations- as natural and intuitive.*" (Regan, 1989:34)

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In contrast to this, the ASSEP is a frequency domain response and, according to Regan (1989:34), a "*deep understanding of the frequency domain is less easily attained*". He continues by stating that the "*main reason for the unease with the frequency domain is that Fourier's frequency domain description is cast in terms of oscillations that persist though infinite time: each sine wave stretches infinitely into the past and the future*" (p. 34). A detailed explanation of the Fourier frequency domain and its contributions are presented by Regan and is beyond the scope of this paper. The process of frequency domain and its utility in the ASSEP hearing estimation will be graphically presented in the following section.

An annotated schematic display of the response following signal presentation is presented below. (Derived from the Cuban Neuroscience Center Power Point presentation on the Audix Multiple Steady State Response, 2000)

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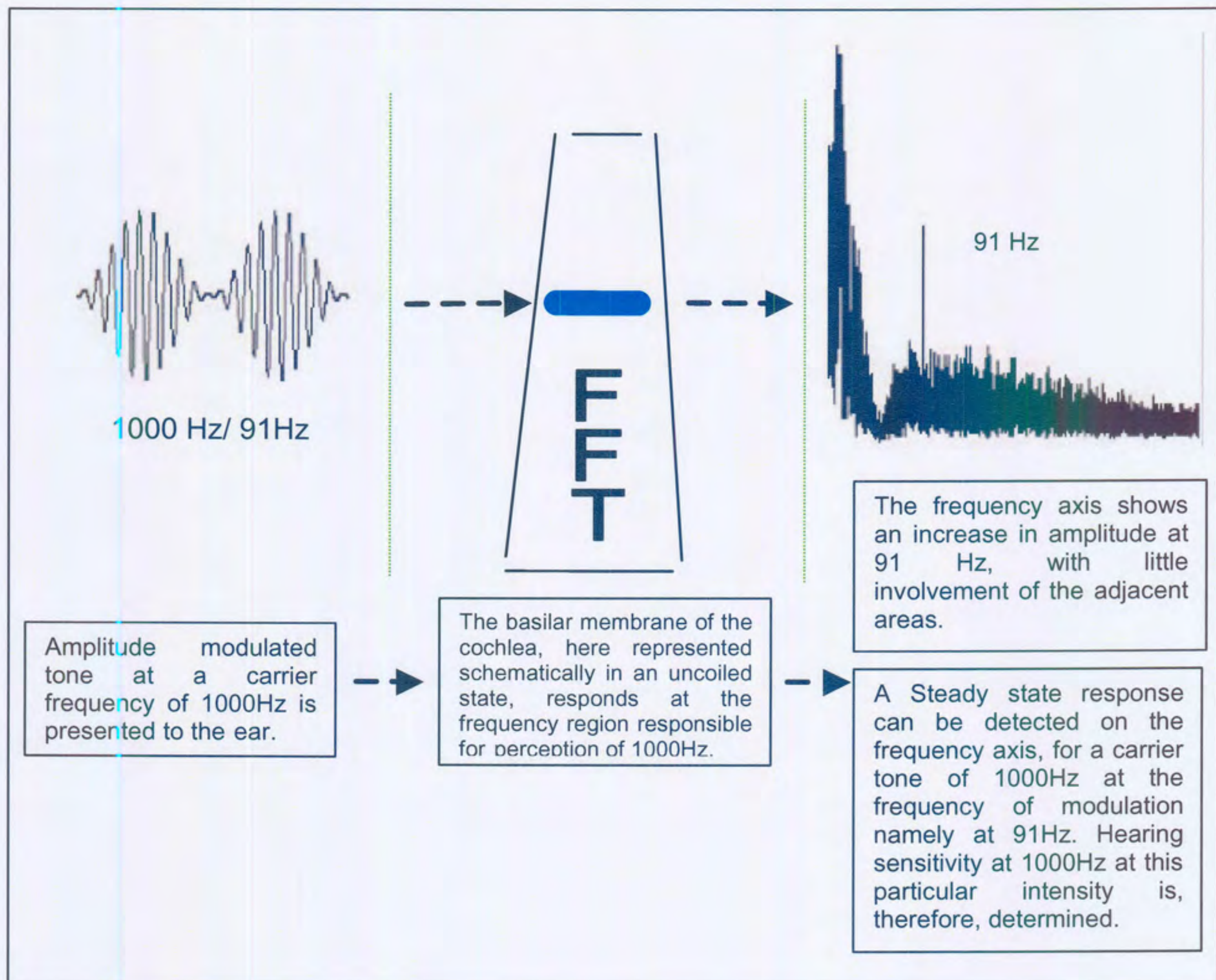

Figure 3.1 **Graphic display of response detection at the frequency of modulation – Phase 1**

Because the stimuli are sustained, the response is ***periodic*** and contains the compounded amplitude information of the fundamental frequency (which is the modulation frequency) and second harmonic frequency components (Kuwada et al., 1986; Chambers et al., 1986; Picton et al., 1987; Rickards et al., 1994).

The response is converted from the time domain to the **frequency domain** through Fast Fourier Transform and is ***automatically detected*** in the frequency domain by the F-test.

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Because the energy of the response resides at the modulation frequency and its first and second harmonics, instantaneous response detection is possible (Levi, Folsom & Dobie, 1993; Rickards et al., 1994; Lins & Picton, 1995; Lins et al., 1996). The process from Fast Fourier Transform to the final response detection is displayed in Figure 3.1.

Automated response detection through Fast Fourier Transform
(Derived from the Cuban Neuroscience Center Power Point presentation on the Audix Multiple Steady State Response,2000)

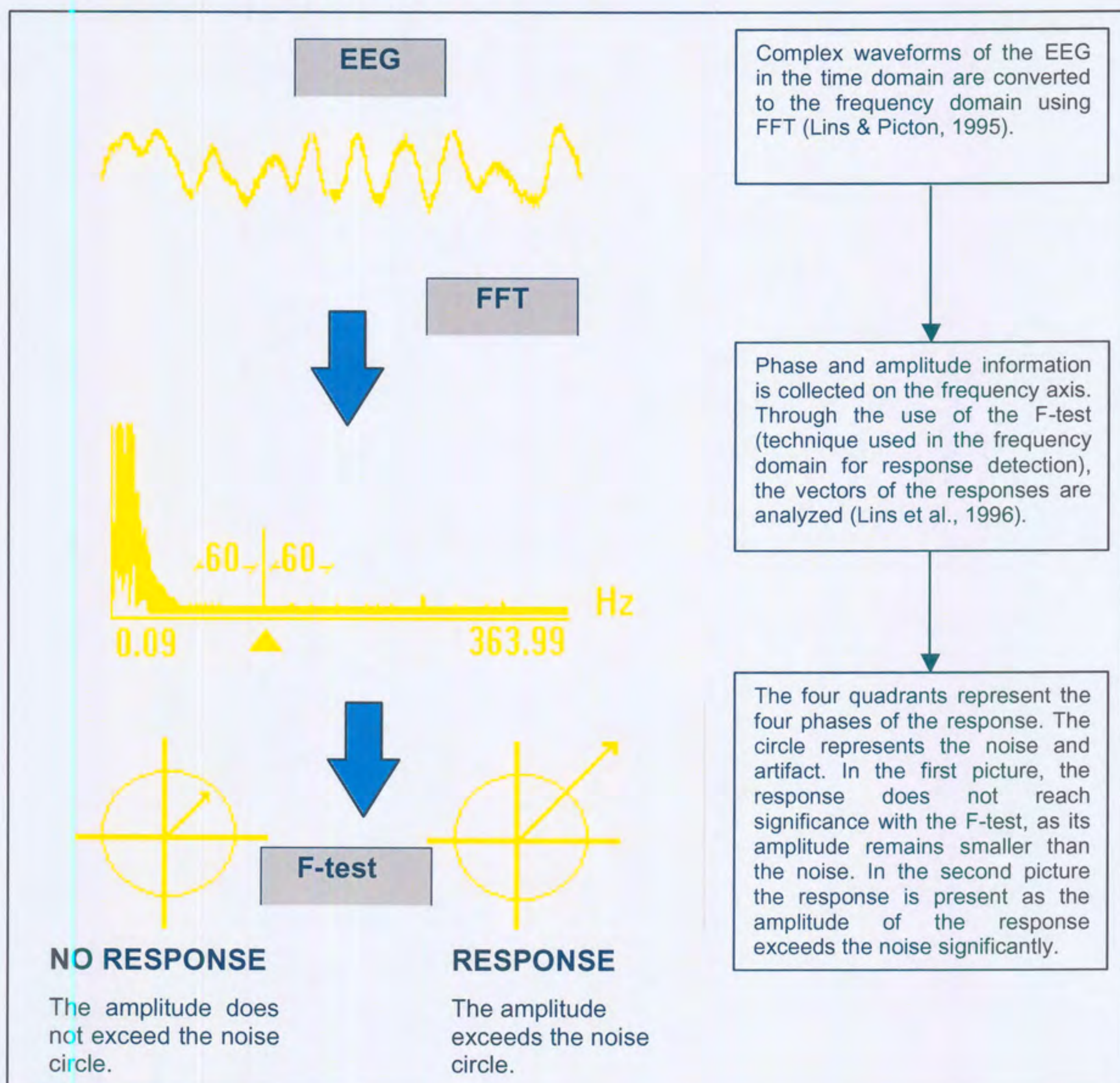

Figure 3.2 Graphic display of response detection at the frequency of modulation – Phase 2

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The transition from the time domain to the frequency domain holds exiting implications for the threshold estimation. The above discussion implies the existence of true objectivity in an AEP protocol. The possibility of automatic detection of a response finally ensures objectivity (the patient is not required to respond and the clinician is not required to interpret) at frequency specific junctures on the audiogram.

The ASSEP moves away from the complex waveforms of the ABR, operating on different principles even though both these short latency responses are inferentially employed to predict hearing sensitivity in difficult-to-test populations (Rance et al., 1995; Lins et al., 1996). The most significant differences are tabulated in Table 3.1.

Table 3.1 Differences between ASSEP and ABR

Characteristic	Auditory Brainstem Response	Steady State Response	Implications for clinical hearing testing
Stimulus	Transient	Sustained	The spectral jitter associated with brief duration stimuli is eliminated with the use of a continuous tone, limiting the amount of useless responses (Rance et al., 1998).
	Click or tone burst	Sinusoidal modulated tone	The frequency specificity of a tone ensures that an audiogram prediction may be obtained while the modulation at 75-110Hz guarantees the objectivity of the recording (Lins & Picton, 1995).
Response	In time domain (msec)	Frequency Domain (Hz)	Response development may be observed at the frequency of modulation and its harmonics, with little interference from surrounding areas (Lins & Picton, 1995).
	Latency and amplitude measurements	Amplitude and phase measurements	The ASSEP technique is restricted to the assessment of hearing. Mass-like retrocochlear lesions may not be identified with variations in inter-peak-latencies in the time domain, as is the case with ABR. The use of ABR in tumor identification has, however, become redundant with the introduction of the CT Scan, MRI and fMRI over the last decades, even though it is still in existence. "With brain imaging becoming the gold standard for diagnosis of neoplasms in the CNS, including the auditory system, diagnostic site-of-lesion audiology tests have become less and less viable" (Jerger, 2000:616).
	Response detection in time domain by clinician	Automatic Response detection at frequency of modulation	The test procedure ensures double objectivity i.e. no subjective participation of the client or interpretation by the clinician (Rickards et al., 1994).

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3.2.3 Final definition

From the above discussion, a definition of the amplitude - modulated Auditory Steady State Evoked Potential can be defined as a periodic response to a periodically changing continuous stimulus at a specific carrier frequency that had been modulated between 3-200Hz depending on the purpose of the ASSEP (Buchwald & Huang, 1975; Kuwada et al., 1986; Picton et al., 1987; Rickards et al., 1994, Lins & Picton, 1995). Based on this definition, some of the key characteristics will be highlighted as they relate to the field of hearing estimation.

3.3 KEY CHARACTERISTICS OF THE STEADY STATE EVOKED POTENTIAL

3.3.1 Steady State Evoked Potentials and stimulus rate

Initially Galambos (Galambos et al., 1981) used the Steady State technique to study responses at 40Hz because of the relatively large amplitudes observed during testing (Cohen et al., 1991). Even though it was a useful neurophysiological tool, the 40Hz responses are affected by various conditions. As in any middle latency responses, maturation plays a decisive role (Osterhammel et al., 1985) and Stapells et al. (1988) reported inconsistent response detection in children. The amplitude of the responses also decreases significantly during sleep (Linden et al., 1985; Cohen, 1991). Moreover, Plourde & Picton (1990) report dramatic attenuation of responses during general anesthesia, limiting its applications in difficult-to-test populations.

The 40Hz Steady State is not without its uses. It can be used successfully in awake adults (>12 years of age) for hearing testing and also as a method to monitor consciousness during general anesthesia. The dramatic effect of sleep and consciousness on the 40Hz responses, however, indicates that the site of generation contains the superimposition of at least two major contributors namely the auditory corti

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being in the lemniscal auditory system of the brainstem with smaller contributions from the primary auditory cortex, hence the lesser susceptibility to sleep and maturational effects (Lins & Picton, 1995).

Quite recently experimental research has been conducted using stimulus rates between 150-190 Hz in an attempt to further investigate the physiology of the auditory system (Lins & Picton, 1995). Even though this technique has not been used in clinical hearing prediction, research results have provided some valuable clues to response generators. Initial findings at the high stimulus rate indicate equal contributions of the brainstem and cortex compared to the relatively larger contribution to responses when the rate is slowed to 80Hz.The variation of the modulation rate offers a novel view of pathology in the auditory system up to cortical level, delineating the various contributions of the lower brainstem, upper brainstem and primary auditory cortex to the processing of sound (Regan, 1989; Regan & Regan, 1993; Lins & Picton, 1995). Research in this regard has, however, not extended beyond hypothesis in most instances.

3.3.2 Steady State Evoked Potentials and stimulus technique

Two kinds of stimulus techniques exist, namely, monotic and dichotic. Rickards et al. (1994) developed the monotic stimulus technique specifically for hearing assessment purposes in a cochlear implant program. As in the case of ABR, the stimulus is presented to each ear sequentially, and for each frequency separately.

The dichotic, multiple stimulus technique was adopted from research related to the visual response field by Regan (1989). Its occasional use in the auditory system was documented by Regan & Regan (1993). They found that when four carrier frequencies are presented in each ear and the stimuli are presented to both ears simultaneously, the

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responses are not significantly different from the responses obtained in the sequential manner. Their findings however, were and still are applicable only to stimuli presented at low to moderate stimulus intensity levels (Lins & Picton, 1995).

In Cuba, the multiple stimulus technique was used in moderate to severe hearing impairment with apparent success (Perez-Abalo et al., 2001). Advocates of the monotic method argue that simultaneous presentation limits the separation of responses at high intensities, while the monotic method provides ear specific information at very high intensities such as will be used in the candidacy determination protocol at a cochlear implant center. The Cuban study holds exiting possibilities that may refute the argument of the sequential advocates. The need for more research is clearly indicated.

3.3.3 Steady State Evoked Potentials and stimulus modulation

Initially, 100% amplitude modulation was considered sufficient, yet researchers in some centers have added various amounts of FM modulation to the stimulus through simple vector addition to create multiple modulation (MM) in their MASTER system. John & Picton (2000) found that 100% AM modulation alone showed no significant responses at 30 dB (approximately 10-15 dB above the behavioural thresholds of their subjects) even though the stimulus was audible to the subjects. The combined stimulus of 100% AM modulation and 25% FM modulation indicated that responses at 50dB reached significance at twice the speed of 100% AM modulation alone (Cohen et al., 1991), while responses at lower intensity levels, such as 30 and 40dB, were enhanced compared to 100% AM alone, therefore increasing the test efficiency even further. It is important to consider that MM increased the test efficiency in addition to the already existing multiple simultaneous stimulation using the MASTER system. The first commercially available system using MM is unavailable at the time of submission, but it is expected to reach

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clinics in 2002. It will be a sequential system based on the endeavors of Rickards and colleagues at the University of Melbourne, Melbourne, Australia.

Multiple modulation needs to be considered with some reservation, however. Although it holds exiting possibilities, further exploration is needed to specify the postulated anatomical origins of the responses and to identify the site of lesion using a multiple modulation technique. AM modulation is mediated by neurons with characteristic frequencies higher than the carrier frequency of the modulation frequency, while FM is mediated by neurons with a lower characteristic frequency (John, Dimitrijevic, Van Roon & Picton, 2000b). The interactions of these two relatively independent processes needs to be defined, as it seems that there is little overlap between the neural generators of AM and FM, especially in the multiple stimulus, simultaneous condition.

With reference to clinical application, it also needs to be confirmed if infants can detect FM modulated signals in the multiple and the monotic stimulus conditions (John & Picton, 2000). The literature indicated FM perception at 4-6 months of age, but these findings need to be clearly confirmed prior to its application in the very young (John & Picton, 2000).

3.4 THE MECHANISM OF STEADY STATE EVOKED POTENTIALS: FROM SIGNAL PERCEPTION TO RESPONSE DETECTION

The mechanism is illustrated in Figure 3.3. The process is arbitrarily divided into the initial rectification process, the derived spectral component, and the FFT and response detection with the F-test.

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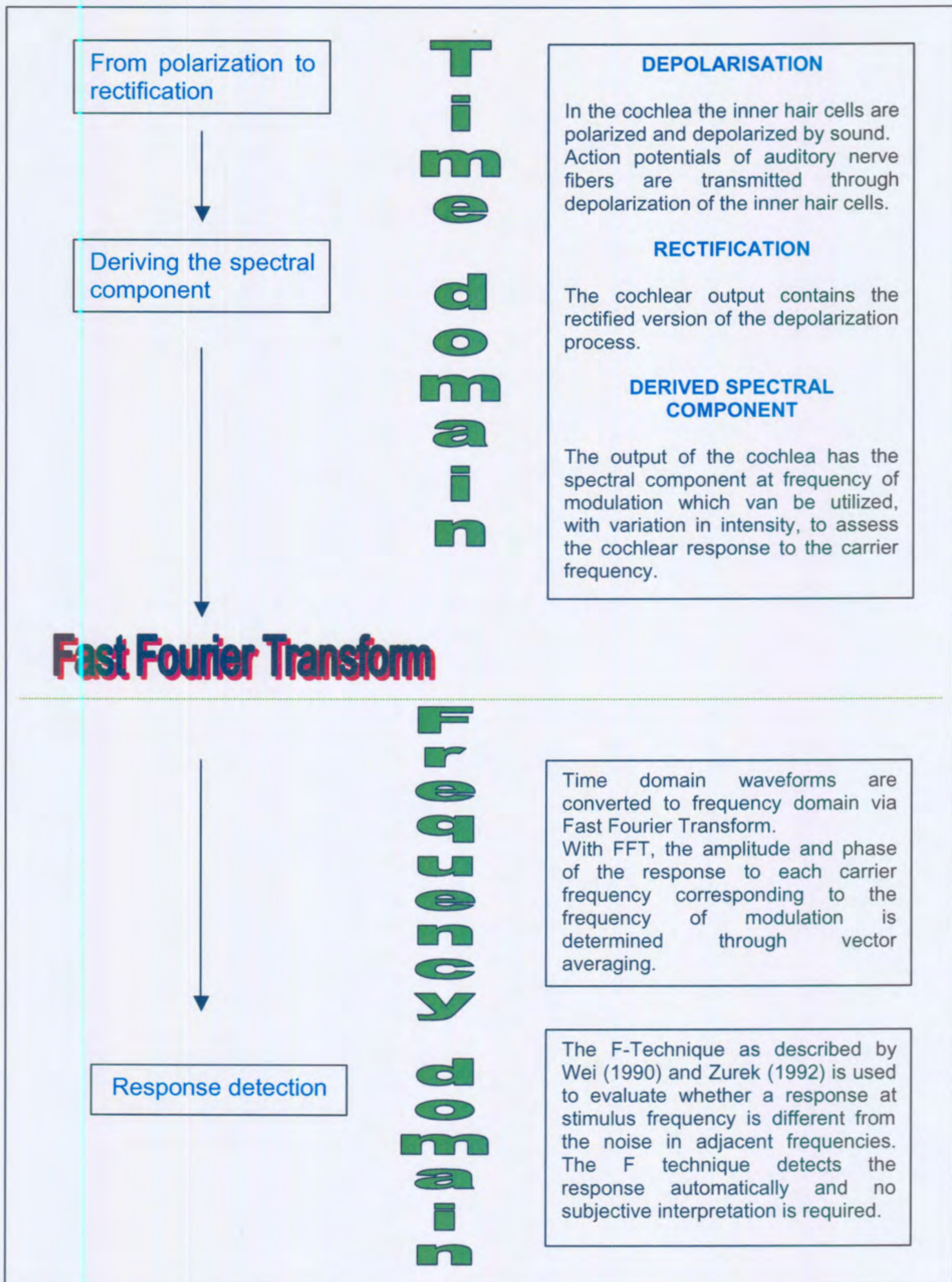

Figure 3.3 **An annotated illustration of the mechanism of ASSEP (Lins & Picton, 1995; Lins et al., 1996; John et al., 2001a & b; John &**

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3.5 THE INFLUENCE OF AUDIOMETRIC AND RELATED VARIABLES ON AUDITORY STEADY STATE EVOKED POTENTIALS

3.5.1 Influence of combined stimulus

Combined stimulus effects are applicable to the dichotic, multiple stimulus mode. The rationale behind combining stimuli deals with the carrier of each stimulus (in other words, the frequency) has its maximal effect at different segments of the basilar membrane, which allow for different groups if inner hair cells to be activated (John & Picton, 2000). The separate modulation frequencies allow for the spectral component of each carrier frequency to be at a different modulation frequency in the frequency domain, provided that the modulation frequencies are an octave apart (Lins & Picton, 1995). Lins & Picton (1995) note that the cochlear filters used in sound perception are somewhat smaller than an octave, still allowing for accurate pitch perception in normal ears. Therefore, outside of an octave, there is little overlap in activation of the areas of the basilar membrane. John & Picton (2000), however, are careful to note that the overlap is not evident at moderate to low intensities.

3.5.2 Influence of frequency domain measurements on latency information

Latency relates to the delay between stimulus onset and the peak of the response (Hood, 1998). Especially in the neurological application of the auditory brainstem response, the use of inter-peak latencies and inter-aural latency measures conveys essential diagnostic information to assist in the identification of mass like lesions on the eighth nerve (Hall, 1992; Hood, 1998; Goldstein & Aldrich, 1999).

There are at least five contributions to the latency of a neuro-physiological response to auditory stimuli, whether recorded in the time domain or in the frequency domain. They are:

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- The acoustic delay of sound
- The transport delay
- Filter build-up time
- Synaptic delay
- Conduction delay (Pantev et al., 1996; John & Picton, 2000).

A further complication derives form the fact that latency is not merely the calculated sum of these five delays. The temporal characteristics and the direction of the field potentials usually influence the relative latency of the response in addition to accentuating onset responses (when synchrony in response is more evident) as opposed to continuous responses.

Because of the multitude of neural excitation patterns in the presence of auditory stimuli, latency interpretation based on physiology is a challenging process. The complex nature of latency measurements has not deterred the accumulation of a wealth of information on latency in the time domain. Because of the periodic nature of the steady state response, however, conventional measurement of latency is prohibited in the frequency domain (Rickards et al., 1994).

Initial research results show latencies in adults of between 11.2 and 14.9 msec, depending on the carrier frequency. Consistent with ABR findings, latency decreases from infancy to adulthood (Osterhammel et al., 1983; Stapells et al., 1989). Decreases in latency are also evident from low to high frequencies, similar to those in adults (Gorga, 1999). A tentative hypothesis by John & Picton (2000) is that the frequency related delay seems to be the sum of transport time and the filter build-up time for each carrier

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frequency. They further suggest that high carrier frequencies show a shorter transport time for acoustic energy to reach the responsive region of the basilar membrane (John & Picton, 2000).

It is expected that the collection of steady state latency correlates will continue in research laboratories. The clinical utility of this information in hearing and neurological clinics may still be elusive in the near future. Nevertheless, the exploration should be encouraged, as the use of true objectivity in latency measurements will amplify existing knowledge of retro-cochlear lesions.

3.5.3 Influence of intensity

As already mentioned, low to moderate intensity stimulus levels show little overlap when modulated one octave apart because the maximum effect of the carrier frequency on the basilar membrane resides at a different location (John & Picton, 2000). However, despite these qualifications, a pattern exists with variation in intensity: When a high intensity stimulus is presented, the basal end of the cochlea dominates while low intensity sounds are mediated by the basilar region responsible for 1kHz perception (John & Picton, 2000). These findings are similar to Zwislocki's statements (1991) that the activation pattern of pure tones on the basilar membrane moves towards the stapes with increase in intensity. He explains this phenomenon by stating that the rise time of the stimulus changes in the post synaptic potential, and the louder the sound, the more rapid the rise-time, resulting in more synaptic transmitter release and more synapses being activated. The stimulus frequency at various intensities also influences the activation of the basilar membrane differently but, irrespective of carrier, saturation may occur at high intensities, adding proof to the non-linearity of intensity changes of stimuli (Lins & Picton, 1995; John & Picton, 2000).

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The clinical implications for hearing estimation are numerous. For instance, the dichotic, multiple stimulus mode, such as used by Perez-Abalo et al. (2001), presents no evidence against overlapping at high intensities. Additionally, the danger of saturation has not been fully explored in terms of clinical signs (Picton, 2001). Furthermore, the effect of multiple stimulation at high intensities runs the risk of noise exposure and noise induced hearing loss (Rickards et al., 2001). It is important to remember that continuous stimulus is provided at high intensity, which may aggravate the risk of noise exposure (Hall & Mueller, 1997). The monotic system also run the risk of over stimulation at high intensity levels and it would be a wise clinical choice to limit the output of the systems. The need for continued research is clearly indicated.

3.5.4 Influence of carrier frequency on Steady State Evoked Potentials

According to John & Picton (2000) there are different physiological mechanisms at work in the generation of a response in low, mid and high frequencies. The high frequency responses occur earlier than low frequencies. They explained this phenomenon by the presence of a traveling wave on the basilar membrane, as well as the transport time of sound to the basilar end of the cochlea for the low frequencies. Generally low frequency responses are lower in amplitude with a lower effective intensity. The lower carrier frequencies evoke an activation pattern on the basilar membrane that covers a greater spatial area than the higher frequencies. Neurons on the rather broad area of the basilar membrane now respond to similar low frequencies such as 500 and 750Hz, and some of the neurons are activated at an earlier stage than others (Moore, 1993; John & Picton, 2000). This phenomenon causes jitter, which can then attenuate the amplitude of the compound response. It implies that better responses are evoked in low frequency regions when the intensity is higher, similar to tone burst ABR at 500Hz (Gorga, 1999;

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Hood, 1998). Higher threshold levels, with greater discrepancy with the pure tone data, could therefore be expected in the low frequencies.

3.5.5 Influence of the modulation frequency (rate of modulation)

In addition to providing the backdrop from which to assess hearing in difficult-to-test populations in various stages of wakefulness and sleep, the rate of modulation is advantageous in the further disentangling of the response generators. Many different regions of the auditory nervous system generate responses that follow the modulation of an amplitude-modulated tone, which has a specific phase and latency relationship with the stimulus (Pantev et al., 1996). It is the overlapping of these responses that is compounded into a scalp recording which is called steady state evoked potentials (Kuwada et al., 1986). The phase and latency measurements remain complicated unless at least one generator is clearly dominant (John & Picton, 2000). Therefore, by manipulating modulation rate or frequency of modulation, some insight may be gained into the generators of steady state evoked potentials.

As mentioned earlier in this chapter (Section 3.3.1), the 40Hz response is generated primarily from the auditory cortex (hence its susceptibility to sleep and anesthesia), with significant variation in response amplitude, while variation in carrier frequency and the brainstem contribute less to this response (Galambos et al., 1981; Cohen et al., 1991). The 80-100Hz responses are sourced mainly from the higher brainstem, the 150-170Hz responses seem to derive from equal contributions from the high and low brainstem (Rickards et al., 1994; Lins & Picton, 1995; John & Picton, 2000).

It could therefore be suggested that within the decision making protocol (Hyde, 1991) propagated in Chapter 2, two different sets of data could be collected by manipulating

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the modulation rate. The increase or decrease of rate could cast light onto the various contributions of the auditory pathway, provided that documented influences such as wakefulness and age are controlled and accommodated within this framework.

3.6 APPLICATION OF AUDITORY STEADY STATE EVOKED POTENTIALS IN DIAGNOSTIC AUDIOLOGY

The clinical tentacles extending from the body of research on steady state evoked potentials seem accelerated. With the influence of information technology it is expected that discovery and application will decease in time frames across fields. Despite these signs of the time, Von Helmholtz (1863:18) warned that "*whoever, in the pursuit of science, seeks after immediate practical utility, may generally rest assured that he will seek in vain*".

His caution is warranted, and most researchers would agree with him. However, the initial findings on clinical application with ASSEP were extremely encouraging, accelerating the process somewhat, as in the words of Thoreau (1820:24) when he commented *"some circumstantial evidence is very strong, as when you find a trout in the milk*".

The following two sections will address the possibilities and the existing research on ASSEP and its relevance to the current study. The application possibilities will be roughly divided into clinical and research applications.

3.6.1 Clinical applications

Clinical applications are currently predominant in the auditory ASSEP literature. It can be gathered that ASSEP research is moving from pure research laboratory studies to more

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applied investigations. Three specific applications will be touched upon: diagnostic testing, screening and the examination of aided thresholds.

The most obvious, and currently most extensively researched application deals with hearing estimation in difficult-to-test populations. The inclusion of ASSEP in the AEP arsenal in hearing assessment holds exciting possibilities in terms of frequency specificity and increased or 'true' objectivity (Rickards et al., 1994; Lins & Picton, 1995; Rance et al., 1995; Perez-Abalo et al., 2001). Especially in the younger populations, the accuracy of the results will have a far-reaching positive effect on the appropriate delineation and initial management of the infant. Not only would the thresholds be more frequency specific and clearly identified, but the intensity levels used in the testing situation could be higher to pinpoint residual hearing in the severe to profound range (Rance et al., 1993; Rickards et al., 1994; Rance et al., 1995). Moreover, the frequency domain also limits the presence of the confounding effect of artifact (Rickards et al., 1994).

With the ASSEP technique, AEP testing moves beyond identification to clear cut diagnosis of hearing acuity problems across the degree and frequency range in all difficult-to-test populations. The variation of the carrier tone, therefore, with a constant range of modulation, enables the recording of, for instance, eight responses simultaneously in the multiple system, provided that there is a four-octave separation between the carrier frequencies in each ear. Threshold predictions may also be obtained for each ear separately. In the words of Picton *"the general wisdom is that it is important to identify an infant with a hearing impairment as soon as possible, preferably within the first few months of life"* (Picton, 1991:3).

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3.6.1.1 Screening

Current proposals for the screening and identification of hearing loss aim to target infants in the first 6 months of life (NIH Consensus Committee, 1993, Joint Committee of Infant Hearing, 1994). Several methods have been proposed, which include OAEs and ABR (White & Behrens, 1993; Hyde et al., 1990). The ASSEP procedure can also be implemented as a screening tool in nurseries. Automatic response detection and frequency specificity are obvious advantages that may be explored successfully in the nursery. The unspecific click stimulus of the ABR and the poor wave morphology associated with tone burst at threshold level may be overcome when using ASSEP as a screening device. Rickards et al. (1994) successfully recorded ASSEP in young, normal full term, sleeping infants in the first few days of life at carrier frequencies 500, 1500 and 4000 Hz. Their use of high modulation showed similar results to unmasked tone burst estimates of adults, with a normal distribution with definite reduction in testing time compared to previously used methods.

3.6.1.2 Aided testing

Once the hearing impairment has been detected in an infant, and the diagnostic procedures to categorize hearing have been concluded, treatment starts. In 16 cases of hearing loss, the initial treatment usually entails the fitting of hearing aids (Picton et al., 1998). According to Picton (1998:329) this procedure is usually "*a matter of luck and intuition*". In older populations, selection and adjustment is based on subjective responses to acoustic stimuli, the so-called functional gain (Hawkins & Haskell, 1982). Real ear insertion gain (Seewald et al., 1985) can be introduced, but the unaided audiogram is required for this purpose. This is often unavailable in difficult-to-test populations. The probe placement for these measurements can also be problematic in the very young or the uncooperative (Picton et al., 1998). The ABR has been introduced

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as a measure of functional gain, yet the brief stimuli show high susceptibility to distortion through the free field speaker and the hearing aid, further complicated by excessive artifact (Kileny, 1981; Hall & Ruth, 1985). The hearing aid is designed to handle rapidly changing sounds, which makes it quite different from the type of stimulus used in ABR testing (Gorga et al., 1985). The prediction of hearing aid performance on continuous speech stimuli is, therefore, challenging when using a brief onset response.

On the other hand, the nature of ASSEP stimuli (regularly repeating) that stabilizes over time is unlikely to distort by amplification through speakers or hearing aids (Galambos et al., 1981; Rickards & Clark, 1984; Stapells, 1984). These measures can also be performed in infants as well as during sleep using a modulation rate between 70-100 Hz (Cohen et al., 1991; Aoyagi et al., 1994; Rickards et al., 1994; Lins & Picton, 1995).

3.6.2 Research applications

There is a multitude of exiting possibilities because the clinical application of this technique is in the initial phase. An experimental endeavor could be to record Steady State Evoked Potentials from the speech processors of the cochlear implants, using an adapter cable, to ensure maximal use of the electrode configuration in the maps. Another application proposes the use of a single carrier tone while varying the modulation frequency. According to Regan (1989) this may provide insight into the non-linear processing in the auditory system. This also holds exciting possibilities for the field of audiology as the processing of sound up to the primary auditory cortex can be examined in a context of binaural stimulation as opposed to monaural stimulation, moving away from hearing to processing of sound.

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Regan & Cartwright (1970) showed that the visual ASSEP to multiple stimuli is recordable and able to be analyzed independently if each stimulus is modulated at a different rate (see Regan, 1989 for detailed descriptions of these endeavors). It would be prudent for researchers occupied with the auditory system to look beyond the application of multiple ASSEP in hearing assessment to auditory processing and also multi-sensory processing. Auditory processing at supra-threshold levels could possibly be explored with variation on modulation rate (John & Picton, 2000) to expand on initial research indicating the origin of responses.

Interaction between the visual and auditory systems in terms of electrophysiological responses has not been researched even though the population with auditory processing disorders often exhibit related difficulty in reading, which is not limited to comprehension but includes mechanics of reading. Integrated treatment approaches are recommended and entail a pen and paper approach to diagnosis. Electrophysiological responses in the visual and auditory modality could become extremely valuable in the quantification of linguistically –independent deficits, particularly in the multilingual South African population. The audiologist may be able to provide a unique service to speech-language therapists by implementing the visual and auditory ASSEP measurements.

A further unique advantage that audiologists have is their access to visual communicators as opposed to auditory communicators, in the deaf population. This holds exciting possibilities for research with ASSEP. The relative contributions of the auditory system as opposed to the visual system in different modes of communication have not been quantified with electrophysiology. Within the electrophysiological test battery, the ASSEP technique in particular could offer exciting objective measures of this

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interesting phenomenon, clarifying some of the highly controversial methodology wars between the so-called manualists and oralists.

3.7 ADVANTAGES OVER AUDITORY BRAINSTEM RESPONSE

Because of the novelty of the technique, clinical research is somewhat limited. Some advantages over ABR have been postulated (Rickards et al., 1994; Lins et al., 1996) even though the techniques have not been compared directly. These include:

3.7.1 Steady state provides objective response detection

Response measurement is simple and automated. This is different from ABR in that an interpreter is not required since no peaks need to be identified. Rance et al. (1993:47) comment on this particular advantage over other evoked potential techniques by stating simply that "*it does not require subjective waveform analysis*". Within the low frequency tone burst ABR, subjectivity is especially rife, as the wave morphology shows clear deterioration at minimal response levels, often hindering clear interpretation. Goldstein & Aldrich (1999:121) state that "*too few real life clinical reports are available to know how often, if ever, the discrepancies from the tone burst threshold have led to incorrect diagnostic or management decisions*". With ASSEP, there is, as already mentioned, double objectivity because no response is required from the patient and no interpretation is required from the researcher/investigator. Moreover, there are clear parameters that automatically indicate the presence or absence of a response at a specific modulation frequency to the noise at the adjacent frequencies and that assess the reliability of responses automatically (Lins et al., 1996). There are also well-established and clearly defined signal and noise estimators.

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Another factor to consider is that amplitudes of response does also not decrease as dramatically in pathological ears as with ABR and response detection at low sensation levels may be more pronounced in pathological ears. The increase in Steady State Response amplitude (within 5dB of the pure tone result) may be ascribed to recruitment (Rance et al., 1998), thereby providing additional clinical information with implications for hearing aid fitting. The benefit for better threshold prediction and amplified threshold prediction are evident.

3.7.2 Steady state accurately determines degree of hearing loss

The ASSEP can be recorded down to 10-20 dB above pure tone thresholds, in any state of wakefulness or sleep, provided that the modulation rate remains above 75Hz (Cohen et al., 1991). Close correlation between pure tones and ASSEP have been documented across the mild to profound range (Rickards et al., 1994; Lins & Picton, 1995; Lins et al., 1996). Within the severe to profound categories, Rance et al. (1995) demonstrated that ABR measurements are insensitive to threshold variation because of maximum output restrictions and artifact concerns on the equipment. The precise determination of residual hearing in cochlear implant candidates is vital (Rance et al., 1993), and, as the ASSEP output extends beyond the range of the ABR without artifact complication, its use within this population is highly successful. Rance et al. (1993) have established that an absent steady state response is a reliable indicator of a profound or total hearing loss, indicating a greater degree of impairment and therefore handicap in terms of access to speech stimuli. It also provides a means for improved aided threshold prediction within the confines of cochlear implant candidacy.

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range critical for speech access, whereas the ABR causes a greater spread of energy into frequencies other than the nominal frequency and requires masking noise to reduce the effect of the spectral splatter caused by the energy.

3.7.5 Steady state results can be presented as an audiogram

The frequency specificity of the continuous tone enables the final results to be presented as a conventional audiogram (Lins et al., 1996). The combination of vital information about the degree and nature of the hearing loss depicted on traditional audiogram and the objectivity of an automatically detected evoked response provide a critical advantage over ABR thresholds. Rance et al. (1995) reports 99% of steady state thresholds to be within 20 dB of the pure tone threshold. 95% of these were within 15dB and a further 82% were within 10 dB of the pure tone audiogram.

3.7.6 Steady state is time efficient

A typical ABR recording requires responses to more or less 48 tracings per client for both ears. For example, from 70dB to 20dB in 10dB- descending- steps would require 6 tracings. Replication of waveforms is also required which would, at the very least, double the number of traces to 12. A similar number of tracings would be required for the tone burst ABR at a single frequency. At the very least 24 tracings per ear would be required to obtain two points on the electrophysiological audiogram.

In the multiple ASSEP technique, four frequencies per ear can be tested simultaneously, thereby reducing the number of recordings (for four frequency specific points on the electrophysiological audiogram) to six for both ears. This can result in reducing the testing time dramatically.

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The possible advantages over the existing ABR protocols are evident, yet clinical research has been limited because of the novelty of the technique. An overview of the clinical research and its limitations will be provided in the next section.

3.8 LIMITATIONS OF CURRENT CLINICAL RESEARCH

Limited data are available on the clinical application of ASSEP. The major studies and their clinical limitations are tabulated in Table 3.2.

Table 3.2 Summary of clinical studies on Steady State Evoked Potentials

Authors	Year	Steady State Technique	Number of subjects	Hearing Status	Limitations
Rickards, Tan, Cohen, Wilson, Drew & Clark	1994	Monotic	337 babies between 1 and 7 days old	Normal hearing	The procedure was limited in intensity level as it was performed for screening purposes.
Rance, Rickards, Cohen, Burton& Clark (AUS)	1993	Monotic	25 children	Severe to profound hearing loss	The full range of degree of hearing loss was not included, and configuration of hearing loss (high, low, mid frequency hearing loss) was not considered
Rance, Dowell, Rickards, Beer & Clark	1998	Monotic	108	Severe-profound hearing loss	The degree of hearing loss was limited, and configuration of hearing loss (high, low, mid frequency hearing loss) was not considered
Johnson & Brown	2001	Monotic	10 subjects	3 normal hearing 7 abnormal hearing	Limited number of subjects who were not representative of the various degrees and configurations of hearing loss
Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez Abalo, Martin & Savio	1996	Dichotic	37	20 normal hearing adults 17 hearing impaired adolescents	The study was conducted at three different sites with different test protocols limiting comparative value The subjects were not representative of the various degrees or configurations of hearing loss
Perez-Abalo, Savio, Torres, Martin, Rodriguez, & Galan	2001	Dichotic	83	43 hearing impaired children 40 normally hearing adults	The spectrum of configuration of hearing loss was not represented and no consideration was given to age and gender effects that are well documented in the evoked potential literature
Lins & Picton	1995	Dichotic	40	Normal hearing	No data on the possible impact on an impaired hearing system
John & Picton	2000	Dichotic	34	Normal hearing	No data on the possible impact on an impaired system
John, Dimitrijevic & Picton	2001	Dichotic	34	Normal hearing	No data on the possible impact on an impaired system
Valdes, Perez-Abalo, Martin, Savio, Sierra, Rodriques & Lins	1997	Dichotic	16	Normal hearing	No data on the possible impact on an impaired system
John, Lins, Boucher & Picton	1998	Dichotic	16	Normal hearing	No data on the possible impact on an impaired system
Herdman & Stapells	2001	Dichotic and Monotic	10	Normal hearing	No data on the possible impact on an impaired system

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In summary the following were observed: in the simultaneous stimulation condition most of the studies focused on normal populations in attempt to further describe the stimulus and recording parameters. Studies conducted in the hearing impaired population were limited in number, severity and degree of hearing impairment. The same was observed in the sequential stimulation condition.

3.9 SUMMARY OF CHAPTER THREE

This chapter has explored Steady State Evoked Potential as a new technique in the prediction of hearing thresholds in difficult-to-test populations. Steady State was defined in a context of short latency responses, some of its key features were highlighted and the mechanism explained. The influences that impact on the type of information obtained with steady state were discussed. The chapter was concluded by discussing the advantages over the ABR, while highlighting the limitations of the technique that will be addressed by this study.

"Whoever, in the pursuit of science, seeks after immediate practical utility, may generally rest assured that he will seek in vain" (Von Helmholtz, 1821-1894).

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CHAPTER FOUR
RESEARCH METHOD

Aim of Chapter

In this chapter, a detailed description of the participants, protocol and procedures of the experiment is presented.

4.1 INTRODUCTION

The quest for a truly objective clinical measure to characterize hearing in normal ears and more especially in ears with hearing loss has been addressed in the preceding chapters as they relate to auditory evoked potentials. The dichotic multiple frequency Steady State Evoked Potential (Mf ASSEP) technique has been shown to be a clinically valid tool in comparison to pure tone audiometry, as discussed in Chapter 3. The comparison between two evoked potential techniques, namely Auditory Brainstem Response (ABR) and Mf ASSEP, has not been addressed in a large sample of normal and impaired ears. **The purpose of this chapter is thus to describe the research method employed in the evaluation of the clinical validity of the dichotic Mf ASSEP technique by comparing it to results obtained from pure tone audiometry and ABR testing in a group of normal ears and ears with hearing loss.**

4.2 AIMS OF THE RESEARCH

The aims of the research are as follows:

4.2.1 Main aim

The main aim of this study was to determine whether thresholds obtained with dichotic Mf ASSEP can translate into an accurate description of hearing acuity when compared to pure tone thresholds and ABR threshold estimates in normal ears and ears with hearing loss.

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The following sub-aims were formulated in order to realize the main aim of the study:

4.2.2 Sub aims

- To determine the comparative effectiveness of Mf ASSEP and the ABR protocols to estimate pure tone thresholds at 0.5,1,2 and 4 kHz in normal ears.
- To determine the comparative effectiveness of dichotic Mf ASSEP and ABR protocols in predicting pure tone thresholds at 0.5,1,2 and 4 kHz in impaired ears controlled for type, degree and configuration of hearing loss.
- To determine the time efficiency of dichotic Mf ASSEP compared to 0.5 kHz tone burst ABR and click-evoked ABR in obtaining pure tone threshold estimates at 0.5 – 4 kHz.

4.3 RESEARCH DESIGN

A comparative experimental research design (Leedy, 1997) was selected for this study. According to Leedy (1997), three basic components need to be addressed in any experimental design. They are the dependent or measured variable, the experimental setting and the independent or manipulated variable. This study investigated the usefulness of the dichotic Mf ASSEP technique in the estimation of hearing compared to an ABR protocol.

The **manipulated variable** for this study was the three test procedures utilized to estimate hearing thresholds. The **measured variable** was the threshold estimations and the time requirement for each procedure. The pure tone hearing thresholds served as the gold standard or reference of hearing against which the threshold estimations using dichotic Mf ASSEP and ABR were compared. A single experimental setting was, therefore, selected to ensure representative data, comparable between independent

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variables. The experimental setting was a **controlled environment** to provide a stable context for investigating the effects of the independent variable (Leedy, 1997). **Controlled variables** were applied to the experimental setting. Controlled variables are factors controlled by the researcher to cancel out or neutralize any effect they may otherwise have on the observed phenomenon. In this study they included aspects such as the age and hearing ability of the subjects.

More specifically the variables of this study are as follows.

Manipulated or independent variables:

- Conventional pure tone audiometry
- Dichotic Multiple frequency Steady State Evoked Potential technique
- An Auditory Brainstem Response with tone burst at 0.5 kHz and click protocol

Measured or dependent variables:

- Pure tone threshold measurements at 0.5, 1, 2 and 4 kHz
- Mf ASSEP threshold estimations at 0.5, 1, 2 and 4 kHz
- ABR threshold estimations at 0.5 kHz for tone burst stimuli and between 1 - 4 kHz (Hall, 1992; Hood, 1998; Gorga, 1999) for click stimuli
- Test time for Mf ASSEP procedure
- Test time for ABR protocol
- Repeated Mf ASSEP threshold measurements for ten normal and four ears with hearing loss

Controlled variables:

- Age
- Gender - an equal gender distribution is proposed
- Hearing ability

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The following figure outlines the research design.

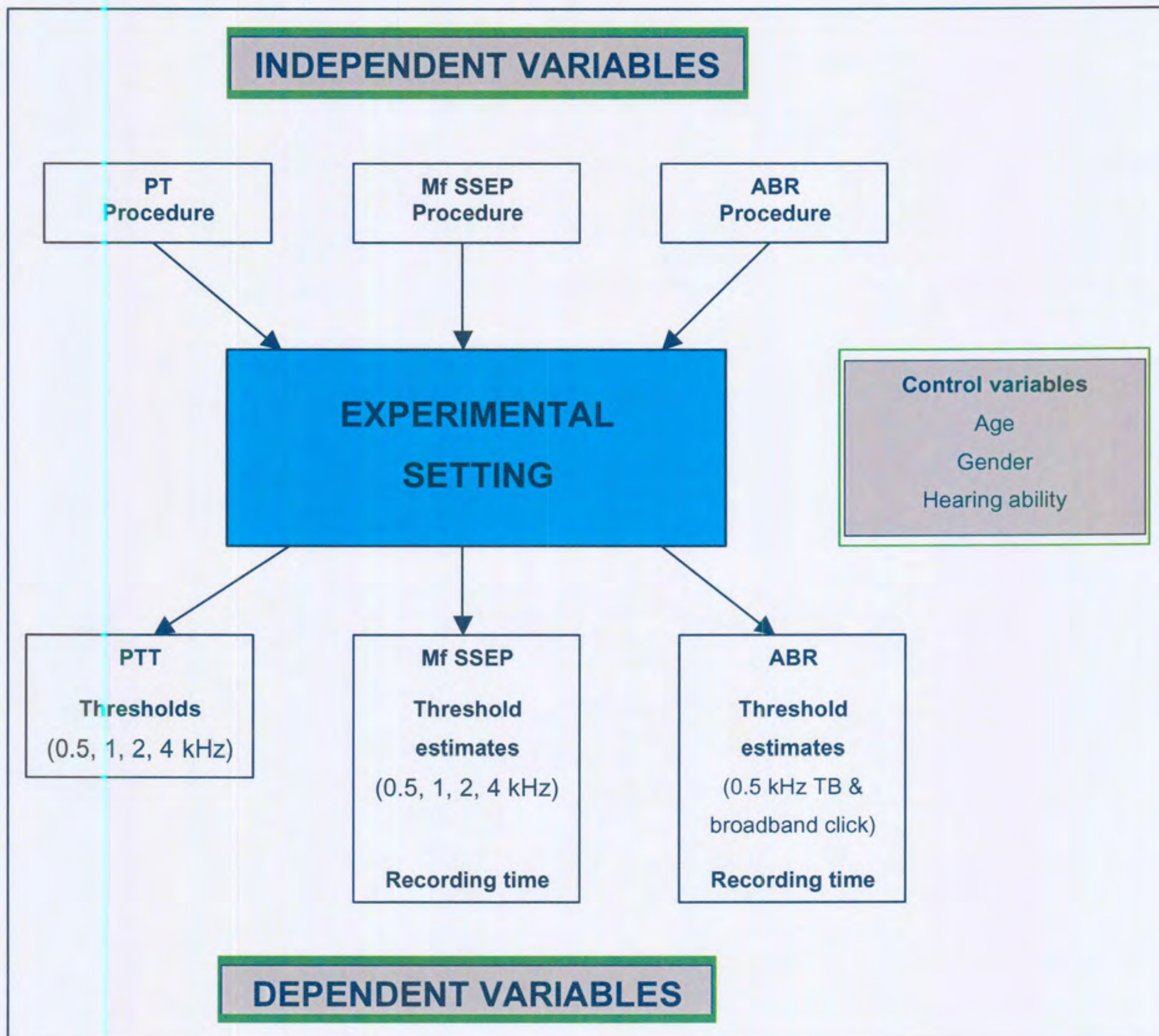

Figure 4.1 Outline of the research design

The procedures (independent variables) will be compared in terms of the correlation of corresponding dichotic Mf ASSEP and ABR threshold estimations (dependent variable) as well as the test time required for each procedure (dependent variable).

In addition, the test-re-test reliability of the dichotic Mf ASSEP was investigated as a separate, unrelated variable. This was incorporated because it is a new clinical

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procedure needing clinical validation, in comparison to the extensive literature on ABR reliability substantiated over the last three decades (Hall, 1992).

The analysis of data consisted of a comparison of pure tone prediction capabilities of the dichotic Mf ASSEP procedure and the ABR protocol by evaluating two indicators:

1) The difference between the PT threshold estimations for each procedure
2) The statistical non-parametric Spearman correlation between corresponding variables. The required test time to complete the dichotic Mf ASSEP procedure and the ABR was analyzed to compare the time-efficiency of the various techniques.

4.4 SUBJECTS

Fifty-five subjects participated in the study. Twenty-eight subjects (56 ears), aged between 17 and 38 years, had normal hearing ability and were recruited from the student body and personnel at the university where the study was conducted. Subjects included 16 males and 12 females. Twenty-five subjects (50 ears) exhibited hearing impairment across the mild to profound range (Goodman, 1965) and configuration (at low, mid and high frequency) of hearing loss (Roeser et al., 2000a) and were between 12 and 21 years of age.

4.4.1 Criteria for the selection of the subjects

Subjects were selected according to the following criteria:

4.4.1.1 Hearing ability

Subjects in the normative group were required to have hearing thresholds equal to or less than 25dB HL across the test frequencies of 0.5, 1, 2, and 4 kHz. Although 0dB HL

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is considered as 'perfect' hearing (Roeser, Buckley & Stickney, 2000a) thresholds between 0-25 dB HL are considered within normal limits for adults (Goodman, 1965).

In the hearing impaired group, an attempt was made to accommodate a variety of degrees of hearing loss with a sensory origin. Subjects had to present with a hearing profile within the range of severity as stipulated by Northern & Downs (1991) of **mild** (26-40 dB), **moderate** (41-55 dB), **moderate-severe** (56-70 dB), **severe** (71-90 dB) or **profound** (91+dB). Within the degree specification, subjects had to present with a variety of configurations of hearing loss adopted from Roeser et al. (2000a). They are: **flat configuration, gradual slope, ski slope, low frequency, notch and high frequency configuration.**

4.4.1.2 Normal middle ear functioning

Any conduction problems caused by middle ear pathology influence the accuracy of the pure tone thresholds, the amplitude of the steady state Responses and the wave latency and morphology of ABR recordings (Hall, 1992; Hood, 1995). Normal middle ear functioning was determined with the otoscope and by obtaining tympanograms. Norms are presented in Section 4.4.2.3 later in this Chapter.

4.4.1.3 Subject age and gender

Teenagers and adults, who would be able to perform reliably in pure tone audiometry, were selected and paired for gender as a reference point of the current study. Their age ranges would not affect the electrophysiological test protocols adversely as studies have shown no significant age effects on the auditory brainstem response for subjects between the ages of 10 and 60 years (Hood, 1998). Although the same vast amount of data are unavailable for the dichotic Mf ASSEP technique, the following assumption was

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made: because the dichotic Mf ASSEP at the modulation rates of the current study have the same characteristics as a short latency response like the ABR, the same general age and gender criteria may be upheld. Subjects were therefore selected to fall within this range. The normative subjects ranged between 17 and 38 years of age, whilst the hearing impaired subjects ranged between 12 and 21 years of age. In the selection of subjects an attempt was made to acquire an even gender distribution across both subject groups to ensure a representative sample. Although small differences occur for brainstem responses in males and females, the clinical importance of this fact is generally minimal because of the substantial normal variability (Hall, 1992).

4.4.2 Subject selection procedures

Non-probability quota sampling (Neuman, 1997) was used in selecting research subjects. According to Neuman (1997), this entails selection within predetermined groups. Availability in terms of time constraints was also considered. The procedure followed in the selection of subjects entailed informed consent by a subject and/or his guardian (Appendix A) following clearance with the University of Pretoria Research Ethics committee, the use of biographical information, and otoscopic examination of the external meatus, tympanometry and pure tone audiometry.

4.4.2.1 Biographical detail

Subjects with normal hearing were selected on the basis of their age, gender and subjective perception of hearing acuity. Their availability to participate in the study was also taken into account.

Subjects with hearing impairment were selected based on their age (between 12-21 years of age), degree of hearing loss (mild to profound), type of hearing loss

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(sensorineural), audiogram configuration (low, high and mid frequency loss) and educational placement. The hearing impaired subjects were all attending a school for the Hard of Hearing where a natural auditory-oral approach is followed. The educational setting was important for two reasons. Firstly, it ensured that the subjects' exposure to sound was equal. Secondly, the subjects' hearing levels (aided and unaided) are regularly monitored to identify any conduction pathology and progressive hearing losses. The fact that appropriate amplification is emphasized in the school setting ensured that the subjects were utilizing their residual hearing optimally.

4.4.2.2 Otoscopic examination

An otoscopic examination was performed on each subject in both ears to determine if any obstruction was visible which could affect the conduction of sound in the outer ear (Ballachanda, 1995; Stach, 1998). The condition of the tympanic membrane and external meatus was also inspected for inflammation, perforation or any other visible abnormalities. If a light reflex is observed, it is often indicative of a healthy tympanic membrane (Hall & Chandler, 1994; Ballachanda, 1995). This procedure lasted approximately 3 minutes.

4.4.2.3 Tympanometry

Middle ear functioning was measured using tympanometry in order to ensure subjects had no middle ear involvement that could influence results (Hall & Chandler, 1994). Therefore values for each ear included in the study had to fall within the normal ranges of a Type A tympanogram (tabulated below).

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Table 4.1 Tympanometry norms for the current study

Ear canal volume	0.5 – 1.5 cc
Compliance	0.3 – 1.6 cc

Source: Stach (1998)

Both ears were evaluated, and the duration for each subject was approximately five minutes.

4.4.2.4 Pure tone audiogram

The data obtained from the pure tone audiogram was used to select normal hearing subjects by determining if their hearing were within the normal range of 0-25dB HL across 0.5-4kHz (Roeser et al., 2000a).

Pure tone audiograms of the subjects with hearing loss were used to determine the degree and configuration of hearing loss. Pure tone audiograms not only formed a part of the selection criteria for subjects but also constituted one of the measured variables for this study as a standard measure to which ASSEP and ABR results were compared. The subjects with hearing impairment underwent pure tone audiometry to confirm previously obtained unaided hearing thresholds. Obtaining a complete pure tone audiogram for a subject took approximately 20 minutes.

The degree of hearing loss was calculated, based on the monaural pure tone average of 500, 1000, 2000 Hz as stipulated in guidelines by Goodman (1965). A modification, however, was made to this pure tone average (PTA) by adding the 4000 Hz threshold in order to ensure an accurate representation of the degree of hearing loss. This is especially necessary with various high frequency configurations, such as a ski-slope, for example, where the PTA based on 0.5, 1, and 2kHz could render a normal PTA when

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the hearing ability of the subject would require amplification in the high frequencies (Goodman, 1965, De Waal, 2000). Each ear was described in terms of an arbitrary low-, mid or high frequency configuration adopted from Roeser et al., (2000a) and categorized within the categories stipulated in Section 4.4.1.1 of low frequency, notch, flat, gradual slope, ski-slope or high frequency configuration based on pure tone results. A detailed description of the distinguishing features of each configuration is given in Table 4.3.

4.5 DESCRIPTION OF SUBJECTS

4.5.1 Subjects with normal hearing – normative group

The normative group of 28 subjects consisted of 12 females and 16 males. Subjects varied between 17 and 38 years of age. Figure 4.2 represents the age and gender distribution of the normal hearing subjects across five age intervals of five years each.

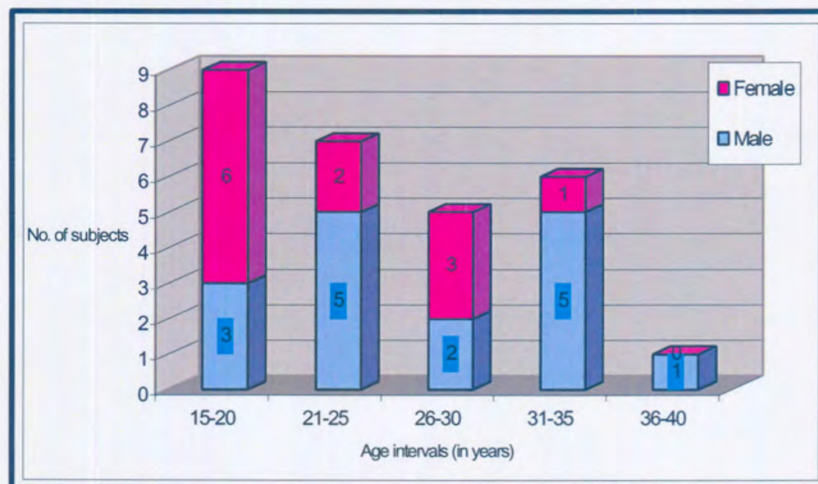

Figure 4.2 Age and gender distribution of subjects in the normative group

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4.5.2 Subjects with hearing impairment – experimental group

All subjects complied with the selection criteria. A description of the subjects is tabulated in Table 4.2 according to subject and Table 4.3 according to ears.

Table 4.2 Classification of subjects with consideration to age, gender, degree and configuration of hearing loss

Subject Age	Subject Gender	Degree of hearing loss		Configuration of hearing loss	
		Left Ear	Right Ear	Left Ear	Right Ear
17.71	Female	Mild	Mild	Flat	Flat
17.24	Female	Moderate	Moderate	Gradual slope	Gradual slope
16.9	Female	Moderate	Moderate	Flat	Flat
16.73	Female	Severe	Severe	Flat	Low frequency
18.36	Female	Mod severe	Moderate	Gradual slope	Gradual slope
18.8	Male	Severe	Severe	Low frequency	Flat
18.38	Female	Moderate	Mild	High frequency	High frequency
17.52	Male	Moderate	Moderate	High frequency	Ski- slope
13.09	Female	Mild	Normal	Flat	Low frequency
17.71	Female	Mild	Severe	Low frequency	Low frequency
16.26	Male	Severe	Severe	Flat	Flat
15.17	Male	Severe	Severe	Gradual slope	Gradual slope
16.84	Female	Mild	Mild	Notch	High frequency
16.68	Female	Moderate-severe	Moderate	Ski slope	Ski slope
18.12	Male	Severe	Severe	Notch	Gradual slope
14.51	Female	Moderate-severe	Mod-severe	Gradual slope	Gradual slope
15.59	Female	Profound	Profound	Gradual slope	Ski-slope
16.91	Male	Severe	Normal	Gradual slope	Flat
16.49	Female	Severe	Profound	Up notch	Flat
13.52	Male	Mild	Normal	Ski slope	Ski slope
12.82	Female	Severe	Profound	Flat	Notch
21.04	Male	Profound	Profound	Ski-slope	Flat
19.03	Female	Profound	Profound	Flat	Flat
17.57	Male	Normal	Profound	Flat	Flat
18.69	Male	Profound	Profound	Flat	Low frequency

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Table 4.3 Distribution pattern for degree and configuration of hearing loss in 50 ears

CLASSIFICATION adopted from Roeser et al (2000)	# Ears with normal PTAs (0-25dB)	# Ears with mild PTAs (26-40 dB)	# Ears with moderate PTAs (41-55 dB)	# Ears with moderate-severe PTAs (56-70 dB)	# Ears with severe PTAs (71-90 dB)	# Ears with profound PTAs more than 91 dB
Flat audiogram No more than 20 dB variation between 0.5 and 4kHz	2	3	2		5	6
Gradual Slope PTTs increase gradually as frequency increases			3	3	4	1
Ski-slope Flat configuration up to 1 kHz with >15 dB PTT decrease in high frequencies	1	1	2	1		2
Low Frequency loss 0.5-1 kHz more impaired than 2-4 kHz	1	1			3	1
Notch Notch shaped loss (also inverse notch) around 1-3 kHz		1			2	1
High Frequency Normal PTT's up to 3kHz with a subsequent steep slope	2	2				

4.6 APPARATUS

The apparatus used to obtain answers to the research questions was as follows:

4.6.1 Subject selection apparatus

- The otoscopic examination of the external meatus and tympanic membrane was performed with a **Heine Mini 2000** otoscope.
- Tympanometric evaluation of the middle ear was performed with a **GSI 33 Middle Ear Analyser**, calibrated January 2001 (Testing was performed February 2001).
- Pure tone thresholds were obtained with a **GSI 60 Clinical Audiometer**, calibrated January 2001. Acoustic stimuli were presented through **TDH-39 supra-aural headphones** in a **double-walled soundproof booth**. The subject responded with a **response button.**

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4.6.2 Data collection apparatus

Pure tone thresholds were obtained with a **GSI 60 Clinical Audiometer**, calibrated January 2001[4]. Acoustic stimuli were presented through **TDH-39 supra-aural headphones** in a **double-walled soundproof booth**. The subject responded with a **response button.**

Dichotic Mf ASSEP and ABR recordings were obtained with the AUDIX system (Neuronic S.A., Havana, Cuba). The equipment (Clinical Edition, 2000) consisted of a specialized hardware component connected to a Pentium microcomputer. The system is operated by a software package specifically designed for the acquisition and analysis of auditory evoked responses (AER) including Mf ASSEP, and ABR to click and tone burst stimuli. Calibration of the AUDIX system acoustic stimuli was performed in January 2001. The AEP measurements were obtained in a single walled soundproof booth using TDH-39 supra-aural earphones to present acoustic signals whilst the subjects were lying on a bed.

4.6.3 Data analysis apparatus

The analysis of data was performed on Excel for Windows (1998).

4.7 DATA COLLECTION PROCEDURES

Four sets of data were collected for each research participant, namely, pure tone thresholds, Mf ASSEP threshold estimates, ABR threshold estimates and the duration of each test procedure. Data from each subject were collected on the same day, commencing with pure tone thresholds (as part of the selection criteria), followed by a

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[4] Data collection was from January 2001 to April 2001

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Mf ASSEP and ABR recording. Data were collected at the Department of Communication Pathology, University of Pretoria.

4.7.1 Preliminary study

4.7.1.1 Aim

A preliminary study was conducted on two subjects with normal hearing to determine clinically accountable stimulus parameters and test procedures.

4.7.1.2 Procedure: Determination of stimulus parameters and recording procedures

Four frequencies were selected to serve as comparative reference points between the three test procedures. Test stimuli included pure tones for standard audiometry, carrier frequencies for ASSEP and tone burst stimuli for ABR testing of 0.5, 1kHz, 2kHz, and 4kHz. They were selected to ensure that high and low frequency information centered on the speech spectrum at comparable reference points.

Tone burst stimuli were initially selected for recording ABRs at comparable frequencies to the Mf ASSEP and PTTs. During the preliminary study, however, it was evident that obtaining ABR thresholds with tone burst stimuli at four frequencies in each ear was extremely time consuming (up to 60 minutes). In addition to the time consuming nature of the tone burst ABRs across the frequency range in both ears, the literature suggests that most clinically employed ABR protocols did not adhere to this procedure (Hood, 1998; Arnold, 2000). It was, therefore, decided to include a 0.5 kHz tone burst stimulus for low frequency information and a broadband click stimulus for high frequency information (Hood, 1998) as the ABR protocol. The literature indicates that click stimuli are still the clinical procedure of choice for high frequency information because of better,

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more robust wave morphology (Gorga, 1999; Arnold, 2000). Thus, to ascertain the clinical value of the Mf ASSEP compared to the clinical value of an ABR protocol, it follows logically to use a clinically representative ABR protocol.

4.7.1.3 Results

The test stimuli selected for this study was based on the findings of the preliminary study for each of the procedures are presented in Table 4.4.

Table 4.4 PTTs, Mf ASSEP and ABR test stimuli

Pure tone audiometry				Steady State Responses				ABR using tone burst	ABR using click
0.5kHz	1kHz	2kHz	4kHz	0.5kHz	1kHz	2kHz	4kHz	0.5kHz	Broadband click

Mf ASSEP stimulus intensity for the preliminary study commenced at 70dB HL. This initial intensity, however, proved to be uncomfortably loud for normally hearing subjects, increasing the EEG noise in the recording. This was most probably due to muscle artifact (Rickards, 2001). Taking this fact into consideration, testing procedures commenced at 50 dB HL for normally hearing subjects.

4.7.2 Data collection procedures using pure tone audiometry

Pure tone air conduction thresholds were obtained for 0.5, 1, 2 and 4 kHz in each ear during subject selection and the collection procedure.

A pure tone air conduction audiogram was obtained for each subject once normal outer and middle ear status was confirmed with otoscopy and tympanometry. The modified Hughson-Westlake technique (1944) (Carhart & Jerger, 1959; Hall & Mueller, 1997) was used, and thresholds were determined descending in 10 dB and ascending in 5dB steps until 50% accurate responses were obtained at a specific dB level.

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4.7.3 Data collection procedures for Mf ASSEP

The second data set obtained for each ear was dichotic Mf ASSEP with procedure duration time.

4.7.3.1 Specification of stimulus parameters for dichotic Mf ASSEP

The following stimulus parameters were used in the determination of Mf ASSEP estimates.

4.7.3.1.1 The selection of the carrier and modulation frequencies

Multiple amplitude modulated tones with selected carrier frequencies of 0.5, 1, 2 and 4 kHz modulated between 80–110Hz at least one octave apart, were used. The four carrier frequencies were selected to ensure representation of high and low frequency information central to the speech spectrum and to provide comparative reference points to pure tone thresholds and the ABR results. The carrier frequencies were 95% amplitude modulated between 80-110Hz because this modulation rate produces a brainstem generated response that shows resistance to sleep and sedation (Lins et al, 1995) The faster rates also exhibit fewer interactions than slower rates of 35-55 Hz (John et al., 1998).

4.7.3.1.2 The selection of dichotic multiple stimulation

Four frequencies were simultaneously evaluated for each ear with the dichotic multiple stimulation technique. Previous research indicated no significant difference in accuracy between single and multiple stimulation for SSEP (Herdman, Picton & Stapells, 2001; Lins & Picton, 1995) or monotic and dichotic stimulation for normal hearing and mild to moderate hearing impairment (Perez-Abalo et al., 2001; Lins & Picton, 1995; John et al., 1998).

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4.7.3.1.3 The selection of the stimulus intensity and threshold criteria

All stimulation commenced at supra-threshold level to obtain clear responses in noise. For the normal subjects, the starting intensity was 50 dB HL using a 10dB step descending method. For research participants with hearing impairment, starting intensity was selected on a case specific basis, usually at 40dB above threshold depending on the degree of hearing loss. Threshold was determined by using a "descending in 10 dB, ascending in 5 dB" method. Threshold was taken as the intensity level where the last response was detected, in other words the minimum response level.

4.7.3.2 Specification of recording parameters for Mf ASSEP

The Mf ASSEP recording was performed subsequent to subject selection.Electrode placement was conducted as follows:

- Electrode discs of Ag/AgCl were fixed with electrolytic paste to the scalp at Cz (postive), Oz (negative) and Fpz (ground). Preliminary results by Mens, Gelders, Van Eeghem, Reijden, Snik & Wouters (2000), postulate high sensitivity with positive Cz placements. Impedance levels were maintained below 3 000 Ohms. For binaural stimulation and recording of Mf ASSEP a standard electrode placement is specified. This placement is selected to provide an equal distance between the electrode placement and both ears, which ensures symmetrical recordings.
- Stimuli were as presented via TDH-39 supra-aural headphones.
- Subjects were requested to lie on a bed in a sound proof booth and not to move or blink. Sleep was encouraged and the nature of the stimuli explained.
- Because one channel is needed for dichotic Mf ASSEP testing, only this operating channel was selected during testing.

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- Stimulation was presented dichotically at supra-threshold intensity of 50 dB HL for normally hearing subjects or at 30-50 dB sensation level for hearing impaired subjects. Initially, The stimulus was presented without recording to adjust research participants to the nature of the sound.
- The bio-electric activity was amplified with a gain of 100 000 and analogue filtered between 30 and 300 Hz. The amplitude of the Mf ASSEP is relatively small, requiring substantial amplification. The response of the amplitude modulated tones expected between 80-110Hz falls within the specified band pass.
- The notch filter was activated at 50Hz to avoid line interference.
- No less than 10 and no more than 40 epochs of 8 192 samples (digitized with a sampling period of 1.37 ms) each, were averaged in a response.
- A Fast Fourier Transform (FFT) was calculated 'online' for each long epoch, thereby averaging the response spectra continuously.
- The presence of a response was determined by using the F-test for hidden periodicity in order to test the amplitude of the spectrum at each modulation frequency against the 120 adjacent bins for significant amplitude difference.
- Artifact rejection was performed with shorter epoch sections of 512 points.
- Amplitude is used as the criteria for rejection. A rejection level of 50 micro Volts was specified to reject any responses with amplitudes greater than the specified value.
- No response was annotated after 40 epochs while the minimum response level for each frequency in each ear was taken as the threshold. The software recorded the test data, and the time of recording (exclusing subject preparation).

A summary of the montage and amplifier parameters is tabulated in Table 4.5.

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Table 4.5 Montage and amplifier parameters

Channel	Active	Reference	Ground	Gain	Low Cut	High Cut	Notch
1	Cz	Pz	Fpz	100 000	30	300	ON

- Hearing level is the standard setting for the stimulus. The recording, however, is also viewed in hearing level as a choice between nHL and SPL, to ensure comparability between the results obtained using ABR and pure tone audiometry.
- No difference was measured between nHL and HL in the sound proof testing condition at the four frequencies of the Mf ASSEP. The recordings were, therefore, transcribed in HL with the assumption that the nHL level did not differ for either evoked potential measurement.

4.7.4 Data collection procedures for ABR

The specifications for the stimulus parameters and recording procedure for the tone burst and click ABR are described below.

4.7.4.1 Specifications for click-evoked ABR

4.7.4.1.1 Montage and amplifier selection

- ABR recordings were performed directly following the Mf ASSEP recording.
- Electrode discs of Ag / AgCl were fixed with electrolytic paste to the scalp at Cz, mastoid ipsilateral (Mip), and mastoid contralateral (Mc). Mip and Mc were alternated as reference and ground depending on the test ear, as it was a single channel recording.
- Impedance was kept below 3 000 Ohms
- Supra-aural TDH-39 earphones were placed on the ears of the subjects
- Subjects were requested to lie on a bed in a sound proof booth and were requested not to move or blink. Sleep was encouraged and the nature of the stimuli explained.

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- Stimulation was presented monotically at supra threshold intensity of 60 dB nHL in the left ear with normally hearing subjects. In the hearing impaired group, a supra threshold starting intensity was attempted at 20-30 dB above threshold depending on the degree of hearing loss. Testing commenced in the better ear and masking with white noise was employed at 30 dB below stimulus intensity with asymmetrical hearing loss.
- The bioelectric activity was amplified with a gain of 100 000 and analogue filtered between 10 and 3 000Hz. The neural responses evoked by click stimuli fall within this band pass (Hood, 1998).
- The notch filter was switched off because the electrical line interference does not have a marked influence on the neural response to click stimuli (Hall, 2001, personal communication). A summary of the montage and amplifier selection is tabulated in Table 4.6.

Table 4.6 Montage and amplifier selection for click-evoked ABR

CHANNEL	ACTIVE	REFERENCE	GROUND	GAIN	LOW CUT	HIGH CUT	NOTCH
1	CZ	Mip	Mc	100 000	10	3000	OFF

4.7.4.1.2 *The selection of stimulus parameters for click-evoked ABR*

The stimulus parameters are presented in Table 4.7.

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Table 4.7 Stimulus parameters for click-evoked ABR

Synchronism	Internal (no external sound generators were used)
Stimulus	Click
Periodic stimulus rate	21.0 Hz (to avoid repetition rates that are multiples of 50Hz that could introduce power-line artifact into the response (Hood, 1998))
Study side	Left or Right
Polarity	Positive (According to Hood (1998) any polarity could be used. The AUDIX equipment manufacturers also recommended the use of a positive (condensation) polarity
Duration of click	0.10 msec
Intensity scale	dB nHL
Output	Left or right
Intensity	Starting intensity normal hearing was 60 dB HL Starting intensity hearing impairment was 20-30 dB HL at supra threshold depending on the degree of hearing loss
Masking noise	Off unless asymmetrical hearing loss with bigger than 40 dB gap between pure tone thresholds
Intensity of masking noise	If required, 30 dB below stimulus

4.6.4.1.3 *The selection of recording procedure for click-evoked ABR*

A summary of the recording procedure is tabulated in Table 4.8.

Table 4.8 Recording procedure for click-evoked ABR

Maximum averages	2000 (According to Hood, 1998, 1000-2000 sweeps is adequate to obtain clear responses)
Window	0.0 - 15.0 ms (Hood, 1998; Bachman & Hall, 1998)
Delay	0 ms
Correlation Co-efficient	0.5 set as the minimum correlation
Standard deviation between background noise and response	2.0 set as the minimum deviation between the noise and the response
Noise rejection level	10.0 set as the maximum energy of noise

- All stimulation commenced at supra-threshold level to obtain clear responses in noise. For the normally hearing subjects, starting intensity was at 60 dB HL using a 10dB step descending method in the left ear.
- For research participants with hearing impairment, starting intensity was selected on a case specific basis, usually at 20-30 dB sensation level depending on the degree of hearing loss and threshold was determine by using a "descending in 10 dB, ascending in 5dB method". Testing commenced in the better ear. Threshold was

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taken as the intensity level where the last response was detected, in other words the minimum response level (MRL).

4.7.4.2 Specification of stimulus parameters for tone burst ABR

4.7.4.2.1 Montage and amplifier selection

- The montage and amplifier selection is identical for the tone burst ABR and the broadband stimuli except for the notch filter that was switched on at 50 Hz to eliminate line interference. The montage and amplifier selection for tone burst ABR is tabulated in Table 4.9.

Table 4.9 Montage and amplifier selection

CHANNEL	ACTIVE	REFERENCE	GROUND	GAIN	LOW CUT	HIGH CUT	NOTCH
1	CZ	Mip	Mc	12000	10	3000	ON

4.7.4.2.2 The selection of stimulus parameters for tone burst ABR

The stimulus parameters are presented in Table 4.10.

Table 4.10 Stimulus parameters for tone burst ABR at 0.5 kHz

Synchronism	Internal (no external sound generators were used)
Stimulus	Tone burst
Periodic stimulus rate	21.0 Hz (to avoid repetition rates that are multiples of 50Hz that could introduce power-line artifact into the response. (Hood, 1998)
Study side	Left or Right
Frequency	0.5 kHz
Duration	6 msec
Rise/ Fall	2.00 msec (Hood, 1998)
Plateau	2 ms (Hood, 1998)
Envelope	Blackman (Hood, 1998; Bachman & Hall, 1998)
Polarity	Negative (According to Hood 1998, any polarity except alternating polarities)
Intensity scale	dB nHL
Output	Left or right
Intensity	Starting intensity normal hearing was 60 dB HL Starting intensity hearing impairment was 20-30 dB HL at supra threshold depending on the degree of hearing loss
Noise	On for intensities above 50 dBHL
Intensity of noise	At 30 dB below stimulus

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4.7.4.2.3 The selection of recording parameters for tone burst ABR

The recording procedure was identical to the ABR using broadband click stimuli except for the recording window and the notch filter. The recording procedure is summarized in Table 4.11.

Table 4.11 Recording parameters for tone burst ABR at 0.5 kHz

Maximum averages	1500 (According to Hood, 1998, 1000-2000 sweeps is adequate to obtain clear responses)
Window	0.0 – 20.0 ms
Delay	0 ms
Correlation co-efficient	0.8 set as the minimum correlation
Standard Deviation of response	2.5 set as the minimum deviation between the noise and the response
Noise rejection level	10.0 set as the maximum energy of noise

- All stimulation commenced at supra-threshold level to obtain clear responses in noise.
- For the normally hearing subjects, starting intensity was 60 dB HL using a "10dB step descending method" in the left ear.
- For the research participants with hearing impairment, starting intensity was selected on a case specific basis, usually at 20-30 dB sensation level depending on the degree of hearing loss and threshold was determine in a "descending in 10 dB, ascending in 5dB" method. Testing commenced in the better ear. Threshold was taken as the intensity level at which the last response was detected, in other words the MRL.

4.8 DATA PREPARATION PROCEDURES

- The interpretation of ABR waveforms, to establish minimum response level and thus threshold, was performed after data recording for research participants. The criterion for threshold detection was taken from Wilson (2000). Interpretation of threshold was conducted by a panel consisting of three clinicians, familiar with the interpretation of

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ABR waveforms using click and tone burst stimuli. A blind study was conducted to ensure no interpreter bias and an agreement of two out of three served as consensus. The results are contained in Appendix B. Having reached agreement of threshold, these values were recorded in a Microsoft Excel (1998) worksheet format along with the PTTs and Mf ASSEP data.

- In order to compare the PTTs, Mf ASSEP and ABR data, consistent arbitrary measure of hearing for all procedures was necessary. Decibel Hearing Level (dB HL) was selected with the reference of zero dB HL as the lowest intensity where normally hearing subjects respond at different frequencies (Stach, 1998). The ABR stimuli were calibrated in nHL for a group of normally hearing listeners within the specific setting (Hall & Mueller, 1997). As already stated, there was no difference between the HL and nHL measurements as specified by ANSI (S3.6-1996) probably because of the sound proof testing conditions. The tone burst data and pure tone data are, therefore, comparable without further calculations. Similar findings were evident between click ABR and pure tones in the 1,2,and 4 kHz frequency range as specified by ANSI (S3.6-1996). Thresholds are compared in dB HL because there was no significant difference between dB nHL intensity scale for ABR stimuli and the dB HL scale of the PTTs and Mf ASSEP stimuli.
- The recording time of each test protocol was documented. The software automatically recorded the recording time for Mf ASSEP testing as well as ABR click and tone burst. The ABR time, however, included two recordings, for click and tone burst stimuli respectively. These two times were summed and recorded in minutes, alongside the pure tone time and the Mf ASSEP recording time. No subject preparation time was taken into account in the time documentation.

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4.9 DATA ANALYSIS

The prepared Microsoft Excel (1998) work sheets were subjected to statistical procedures. Parametric procedures using descriptive statistics (central tendencies and correlation) were used on the complete data set while non-parametric statistical procedures (Spearman Rank order correlation) were performed on the threshold data of the hearing impaired group as a whole as well as on the degree and configuration categories.

4.10 DATA PROCESSING

The means and standard deviations, the mean differences and their standard deviations, the normal distributions as well as the non-parametric correlation was tabulated or graphically displayed in figures.

4.11 SUMMARY OF CHAPTER FOUR

The chapter has provided a detailed description of the research method employed in the study. An outline of the main aim and sub-aims of the study was followed by the experimental design, selection criteria and description of subjects. After a description of the subjects, the apparatus for the subject selection, data collection and data analysis were introduced, followed by the procedures employed to collect data using the three specified audiometric techniques. Chapter 4 concluded with the data preparation, analysis and processing methods that were employed to clarify findings.

Comparison is the key to all research (Neuman, 1997).

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CHAPTER FIVE
RESULTS OF THE STUDY

Aim of Chapter

The results obtained from the study will be presented within the perspective of diagnostic audiological procedures.

5.1 INTRODUCTION

The purpose of all diagnostic procedures is aptly summarized by Roeser and colleagues when they state that: *"All diagnostic procedures, whether for the auditory system or any other system, are designed to identify the presence of a disorder as early as possible. When indicated, diagnostic procedures can also help to identify the cause or the nature of the disorder. The value of a diagnostic test depends on the ability to perform as intended"* (Roeser, Valente & Hosford-Dunn, 2000b:12)

In this chapter, results from the experimental comparison of three diagnostic procedures, the pure tone test, the Mf ASSEP and the ABR will be presented in relation to the aims formulated for the study. Within the context of diagnostic audiometric procedures, the main of the aim of the study was to determine whether thresholds obtained with dichotic Mf ASSEP can translate into an accurate description of hearing acuity when compared to pure tone thresholds and ABR threshold estimates in normal and impaired ears. To realize the main aim, the following sub-aims were formulated:

- To determine the comparative effectiveness of Mf ASSEP and the ABR protocols to estimate pure tone thresholds at 0.5,1,2 and 4 kHz in normal ears.
- To determine the comparative effectiveness of dichotic Mf ASSEP and ABR protocols in predicting pure tone thresholds at 0.5,1.2. and 4 kHz in impaired ears controlled for type, degree and configuration of hearing loss.

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- To determine the time efficiency of dichotic Mf ASSEP compared to an ABR protocol (0.5 kHz tone burst and click) in obtaining pure tone threshold estimates at 0.5 – 4 kHz.

Data obtained from the normally hearing ears are discussed first and will serve as a departure point for the results obtained from the ears with impaired hearing. The latter will be presented in a hierarchical order: the statistical procedures (e.g. central tendencies, standard deviations, correlations, demographic factors, degree and configuration effects) of the whole group will be discussed, followed by data obtained in the stipulated degree and configuration categories of the study. The section will conclude with specific case studies to indicate where accurate and inaccurate thresholds were obtained in two of the configuration categories[5].

5.2 RESULTS OBTAINED FOR NORMAL EARS

One of the critical outcomes of any research endeavour is the achievement of comparisons, which, according to Neuman (1997), is the key to all research. While the importance of comparative value is stressed, research should also attempt corroboration of similar and related findings in the literature and provide a framework for secondary levels of comparison and corroboration based on preliminary results.

---

[5] Short abbreviation reminder

Mf ASSEP	Multiple frequency Auditory Steady State Evoked Potential
ABR TB at 500 Hz	Auditory Brainstem Response evoked with 500 Hz tone burst
ABR click	Click- evoked Auditory Brainstem Response using click stimuli
FFT	Fast Fourier Transform
F-test	Technique for automatic response detection

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In the current study, research commenced with a preliminary study (see paragraph 4.6.1 of the method) with normally hearing subjects to determine which recording conditions in the literature would ensure optimal data collection in the specific clinical setting of the current study. After the determination of optimal test parameters, the three test protocols were then performed on normally hearing ears. This endeavour sought to establish equitable points of comparison with existing literature and corroboration of findings where applicable. The most critical application of the data on normal ears was, however, to provide a suitable control for the valid interpretation of data for the ears with impairment.

The results obtained from the control group will be presented as follows: the **accuracy** of the Mf ASSEP to predict pure tone thresholds when compared to an ABR test protocol will be addressed first while the comparative **time efficiency** of the two electrophysiological procedures to obtain threshold predictions will be addressed in conjunction with the data obtained from the ears with impairment.

5.2.1 An assessment of the threshold prediction of MF ASSEP in normally hearing ears

The entire study commenced with the collection of pure tone data for the normally hearing subjects, followed by the electrophysiological procedures. The mean thresholds for each test protocol and the differences between test protocols will be presented. A graphic display of the mean thresholds obtained for each test condition (pure tone thresholds at 0.5 - 4.0 kHz, threshold estimations of Mf ASSEP at 0.5-4.0 kHz, and estimations of the ABR protocol at 0.5 kHz tone burst and click threshold) is tabulated in Table 5.1.

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Table 5.1 **Threshold values of normally hearing ears (n 27) obtained in three testing protocols.**

Frequency (where applicable)	Pure tone threshold in dB HL	Standard deviation	Mf ASSEP in dB HL	Standard deviation	ABR in dB HL	Standard deviation
0.5 kHz	5	+/- 5	33	+/- 11	29[6]	+/- 16
1.0 kHz	4	+/- 5	34	+/- 11	6[7]	+/- 7
2.0 kHz	5	+/- 5	32	+/- 11		
4.0 kHz	5	+/- 6	30	+/- 11		

Source: Appendix A

The results indicate that the pure tone thresholds fall within the upper range of normality with 75% of thresholds ranging between 0 and 5 dB and 88% falling within 0-10 dB. Click ABR MRLs occurred between 9 –23 dB. Despite its inherent limitation in predicting frequency specific hearing estimates, it remains a highly constructive measurement in the absence of high frequency behavioral thresholds, albeit surrounding a single energy point at 3.0 kHz (Weber, 1994; Hood, 1998, Pratt & Sohmer, 1978; Kileny & Magathan, 1987; Hyde, 1991).

The electrophysiological procedures determining *frequency specific hearing* estimates namely the Mf ASSEP MRLs (0.5 –4 kHz) and the ABR tone burst at 0.5 kHz showed an approximately 30-dB elevation from the pure tone results. Although the Mf ASSEP were marginally higher than the tone burst ABR threshold estimate, the larger standard deviation evident in the ABR tone burst threshold points toward greater variability in threshold detection evident in a range of 13 –45 dB. The Mf ASSEP occurred between 19-45 dB.

[6] ABR with tone burst stimuli at 0.5 kHz

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Because of the novelty of the Mf ASSEP technique as a clinical tool in threshold prediction, the results were examined in greater detail. The distribution pattern in relation to the pure tone reference, as well as the difference between thresholds across the frequency range, are presented in the following section.

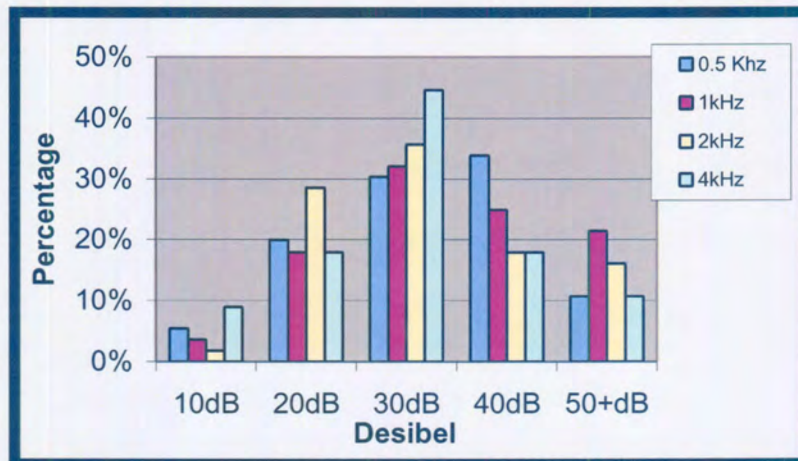

Figure 5.1 Mf ASSEP distribution of 0.5- 4.0 kHz in decibel hearing level

In Figure 5.1, the percentages of the threshold estimates at the four frequencies are represented as bars in 10 dB increments in decibel. The figure indicates that the majority of Mf ASSEP predictions fall within 40 dB of the pure tone thresholds at each frequency. The 0.5, 2 and 4 kHz thresholds showed a sharp decline at the category representing predictions that were more than 50dB from the pure tone threshold. A small number of thresholds were evident within 10 dB of the pure tone. The 1.0 kHz thresholds were also most represented within 40 dB of the pure tone, but the decline after 40 dB was not as dramatic as with 0.5 kHz.

[7] Click evoked ABR

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To determine the effective accuracy of each electrophysiological procedure in predicting normal hearing, the difference in decibel between the pure tones and the MRLs in each condition was calculated. The findings are displayed in Figures 5.2, 5.3 and 5.4.

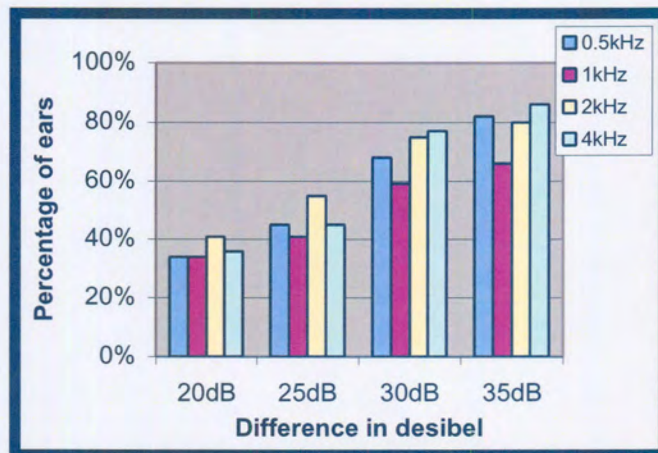

Figure 5.2 Difference between pure tone and Mf ASSEP across frequencies

This figure indicated that the Mf ASSEP threshold predictions showed the highest percentage to be within 35 dB of the pure tone levels. A similar finding was identified when the difference was calculated between the pure tone threshold at 0.5 and the tone burst ABR as indicated below.

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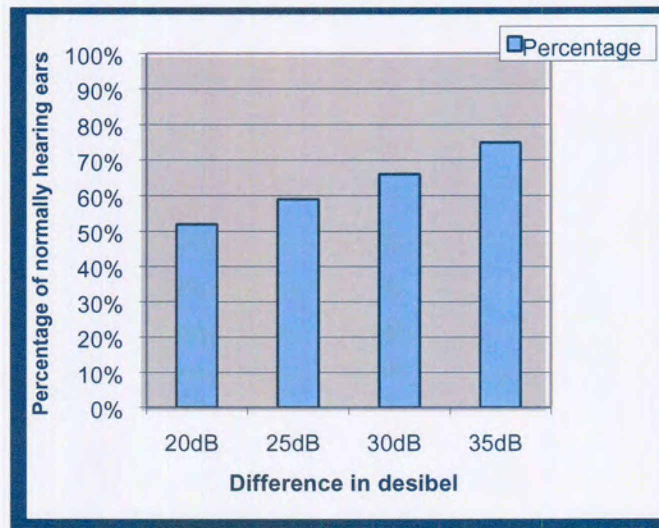

Figure 5.3 Difference between pure tone and ABR tone burst at 0.5 kHz

This figure indicated that 50 % of the threshold estimates using tone burst ABR were within 20 dB of the pure tone at 0.5 kHz while all threshold estimates were within 35 dB of the pure tone. This finding was similar to the Mf ASSEP, albeit only one frequency point across the spectrum.

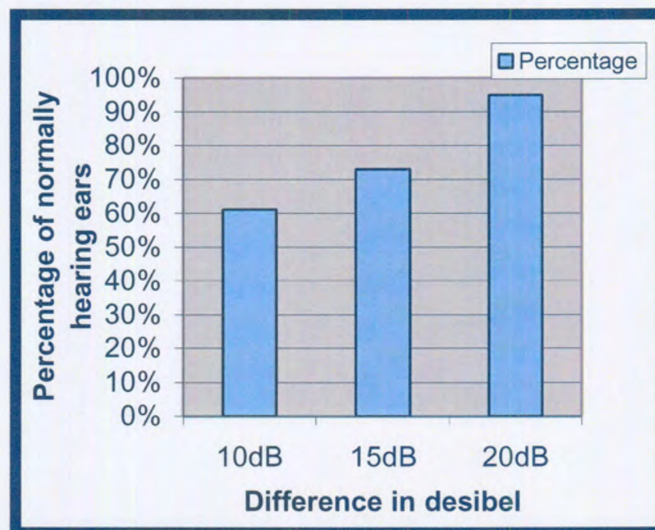

Figure 5.4 Difference between pure tone at 2 and 4 kHz and click-evoked ABR

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As seen in Figure 5.4, the click ABR showed the closest approximation to pure tone high frequency levels as thresholds were estimated to within 20 dB of the pure tone at 2 and 4 kHz. The increased neural synchrony brought on by a broadband stimulus like a click is clearly evident in the closer approximation of the click ABR to the pure tone results.

A review of the current findings within the context of related publications shows satisfactory agreement. When compared to similar studies[8] conducted on normal ears (Aoyagi et al., 1994; Lins et al., 1995, Picton et al., 1998; Perez-Abalo et al., 2001; Herdman & Stapells, 2001) thresholds were similar and show similar results. For instance, the range of 30-34 dB HL of the current study corresponds well with the 29dB threshold obtained by Aoyagi et al. (1994) for 1 kHz carrier frequency, while Lins & Picton (1995) reported an average threshold of 31 dB HL for 0.5 kHz and 25 dB HL for 2 kHz in their research. A further study by John et al. (1998) used identical four carrier frequencies to the current study with monaural stimulation and found slightly lower threshold values of 20,29,19 and 17 dB respectively.

5.3 RESULTS OBTAINED FOR EARS WITH HEARING LOSS – A DESCRIPTION OF WHOLE GROUP DATA IN TERMS OF ACCURACY AND TIME EFFICIENCY

5.3.1 Assessment of Mf ASSEP and ABR in predicting pure tone thresholds

5.3.1.1 Mean values

Even though it was attempted to select equal numbers of subjects across the parameters of the study, whole group analysis determined that the most represented degree of hearing loss was moderate-severe, with a gradual slope in configuration. The

[8] The literature that is reviewed in this section only considers studies that employed a multiple (not the monaural) stimulus technique.

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average age of the subjects was 16 years, while the two genders were equally represented. The average audiogram for all hearing impaired ears for pure tone, Mf ASSEP and ABR thresholds (click and tone burst) is presented in Figure 5.5 and the actual threshold intensities are tabulated in Table 5.2.

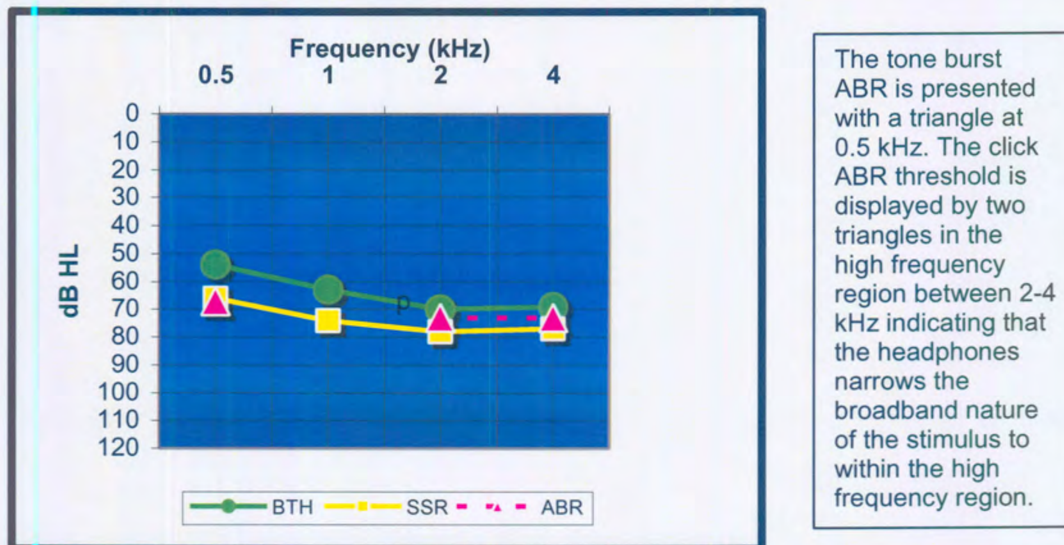

Figure 5.5 Average audiogram for 50 impaired ears in three test conditions (pure tone testing, Mf ASSEP and an ABR protocol).

The average audiogram indicates that a severe, flat hearing loss was the most represented in the group with all electrophysiological techniques displaying satisfactory approximation of the pure tone thresholds across the frequency range. The actual intensities (in dB HL) of audiogram are tabulated in Table 5.2 below.

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Table 5.2 Average intensities of threshold points in the three test conditions.

Frequency	Pure tone threshold	Standard deviation	Mf ASSEP	Standard deviation	ABR	Standard deviation
0.5 kHz	54	+/- 32	66	+/- 23	67	+/- 22
1.0 kHz	63	+/- 32	74	+/- 24	73[9]	+/- 23
2.0 kHz	70	+/- 30	78	+/- 24		
4.0 kHz	69	+/- 29	77	+/- 24		

Figure 5.5 and Table 5.2 indicate that there is no difference between ABR TB at 0.5 kHz and the Mf ASSEP at 0.5 kHz threshold estimations. The ABR click showed closer approximation to the pure tone thresholds in the high frequency regions, however, with a sacrifice of frequency specificity because of the transient nature of the click signal. Standard deviations ranged between 22 and 32 at each threshold point in the study, which is, as Picton et al. (1998) state, acceptable but not ideal.

Differences in threshold between the three test conditions are presented in Table 5.3 as far as frequency specific comparisons could be drawn. The ABR click data are, therefore, eliminated from this discussion.

Table 5.3 Difference in threshold at comparative frequency points

Difference in threshold at comparative frequency points			
Pure tone threshold and Mf ASSEP at 0.5-4.0 kHz		Pure tone threshold and ABR TB at 0.5 kHz	Mf ASSEP and ABR TB threshold at 0.5 kHz
0.5	14	24	9
1.0	18		
2.0	15		
4.0	14		

The smallest difference, based on the data for the whole group, was evident when the two electrophysiological test procedures were compared (9 dB). While this comparison may not be the most obvious, it indicates that within frequency specific procedures within

[9] The ABR protocol is tabulated as the value obtained with tone burst at 0.5 kHz and the click information is presented in the 1.0-4.0 kHz cell.

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the electrophysiological domain, variation exists, even though both are short latency responses. The 14 – 18 dB difference between behavioral threshold and Mf ASSEP thresholds is somewhat higher than reported in the studies conducted by Lins et al. (1996), but still significantly smaller than the tone burst ABR and pure tone difference of 24 dB HL.

5.3.1.2 Correlation

Spearman correlation was executed on the three test protocols and the results are tabulated in Tables 5.4 - 5.8.

Table 5.4 Correlation between pure tone thresholds and Mf ASSEP MRLs at four frequency points.

Frequency	Spearman	p-level	Significance
0.5 kHz	.8803	< 0.01	Significant
1.0 kHz	.8425	< 0.01	Significant
2.0 kHz	.9103	< 0.01	Significant
4.0 kHz	.8612	< 0.01	Significant

Encouraging correlations of above 80% were evident between pure tones and MF ASSEP across the frequency range of the study, indicating that for the impaired group as a whole the Mf ASSEP in the multiple stimuli condition correlates significantly with the pure tone gold standard. This indicates (at a micro level) that, irrespective of the location of the place of perception on the basilar membrane and (at a macro level) therefore, irrespective of the frequency spectrum of our measurement techniques, the Mf ASSEP approximates the specific frequency accurately and without interference from surrounding frequency points. The highest correlation of 90% was observed at 2 kHz, and it may be related to the fact that most of the hearing loss configurations showed a loss in hearing sensitivity at 2 kHz. The largest representation of hearing loss in the experimental group was, furthermore, the moderate severe gradual slope. The 2 kHz

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point would be affected with a gradual slope and the moderate severe category (50-70 dB) would indicate that intensity on the higher side of the spectrum does not influence the accuracy of correlation based on the results obtained from 50 ears.

Table 5.5 Correlation between pure tone thresholds and ABR TB MRLs at 0.5kHz

Frequency	Spearman	p-level	Significance
0.5 kHz	.7695	< 0.01	Significant
1.0 kHz	.6891	< 0.01	Significant
2.0 kHz	.5231	.0015	Not significant
4.0 kHz	.3414	.0558	Not significant

The highest correlation was evident at 0.5 kHz, yet the ABR TB protocol employed in the study showed further significant correlation at 1.0 kHz. This indicates that the tone burst is not as frequency specific as the Mf ASSEP and that interference across the frequency spectrum is evident. While the results will be discussed in detail in the concluding sections of the chapter, two influences should be mentioned here. The first relates to the software and latter to the impaired ear itself.

The tone burst protocol (Table 4.10 of Research Method) included Blackman ramping and masking of the non-test ear, but notched noise was not available on the equipment at the time of testing. Oates & Stapells (1998) and Gorga (1999) have proved that the introduction of notched noise in the tone burst set-up assists in the elimination of energy spreading to nearby frequencies. This may have influenced the spread of the energy at 0.5 kHz to the adjacent frequency.

Another influence may be the presence of abnormal tuning curves in the cochlea, caused by impairment. Picton et al. (1998) found that the presence of abnormal tuning curves in the cochlea causes the impaired system to have place and frequency

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specificity comparisons for lower and higher intensity stimuli. The higher frequencies are not as affected. The low frequencies, however, may be mediated by higher frequency regions on the basilar membrane (sound has to travel via the high frequency region to the low frequency region) and, without strenuous manipulation of the collection parameters, may influence the spread of energy on the basilar membrane. Combined with the absence of notched noise in the software, this may offer an explanation for the correlation of the 0.5 kHz data with other frequencies.

Table 5.6 Correlation between pure tone thresholds and ABR click

Frequency	Spearman	p-level	Significance
0.5 kHz	.5757	< 0.01	Significant
1.0 kHz	.6114	< 0.01	Significant
2.0 kHz	.7009	< 0.01	Significant
4.0 kHz	.6550	< 0.01	Significant

Significant correlation was evident at all frequencies when compared to the click ABR. Very little frequency specific information may thus be derived from the click stimulus. While the use of a headphone transducer certainly ensures that the highest correlation was present at the 2 and 4 kHz points, the other frequency correlation clearly cautions against the use of click ABR as the only technique in predicting hearing sensitivity in difficult-to-test populations.

Table 5.7 Correlation between electrophysiological thresholds with Mf ASSEP 0.5 – 4.0 kHz) and ABR tone burst stimuli at 0.5kHz

Frequency	Spearman	p-level	Significance
0.5 kHz	.7695	< 0.01	Significant
1.0 kHz	.6891	< 0.01	Significant
2.0 kHz	.5231	.0015	Not significant
4.0 kHz	.2889	.1612	Not significant

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Significant correlation was observed at the lower frequencies yet the data point at 2 kHz also showed correlation. The introduction of notched noise is, therefore, a valid consideration to determine whether the spread could be contained to one frequency. This pattern is similar to the one observed in the correlation between the pure tones and tone burst ABR at 500Hz.

Table 5.8 Correlation between electrophysiological thresholds with Mf ASSEP (0.5-4.0 kHz) and ABR click stimuli

Frequency	Spearman	p-level	Significance
0.5 kHz	.4392	.0040	Significant
1.0 kHz	.5896	.0000	Significant
2.0 kHz	.5824	.0003	Significant
4.0 kHz	.6239	.0001	Significant

Mf ASSEP showed the poorest comparative correlation with click ABR yet all four calculations were significant. The presence of a 'transducer effect' was limited although it seems that the 1-4 kHz region showed better correlation than 500Hz.

5.3.1.3 Age and gender effects on whole group data

The gender and age data are presented in Appendix B. Gender effects were evident in behavioral thresholds at 1.2 and 4 kHz and with ABR using click ($p<0.01$) Age effects were not present in any of the testing conditions. The range of ages included in the impaired group was 12- 21 years of age, limiting the age variation.

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5.4 ESTIMATION OF TIME EFFICIENCY – CONTROL AND EXPERIMENTAL GROUP

Roeser et al. highlight a salient and contentious issue when they state...*"Because of time and reimbursement constraints, that which is ideal may not be what is real. The question arises as to which tests are preferred in clinical practice; the answer has to do with efficiency."* (2000b:14). The time consideration was, therefore, one of the critical areas of examination to determine how the electrophysiological test protocols perform in terms of time efficiency. Especially in the difficult-to-test populations, the time variable becomes critical and influences the selection and ordering of test procedures dramatically. While the current study did not deal with uncooperative research participants, the time for each procedure was calculated to determine the range of duration. The value of this calculation resides in the amount of time it requires to obtain the maximum amount of diagnostically applicable information between three test procedures. Within the control group:

- The average pure tone audiogram (otoscopy, immittance air and/or bone conduction)[10] in the normal group took **17 minutes**
- The Mf ASSEP procedure ranged from **12-52 minutes**
- The ABR click and tone burst protocol ranged from **14-54 minutes**.

There was little difference between the two electrophysiological procedures; however, the amount of information gleaned from each procedure shows significant differences. The Mf ASSEP entails a 4-frequency audiogram estimate in each ear, and the data analysis occurred on line (i.e. automatic response detection). The ABR showed one frequency point and one high frequency estimate in each ear, and in the amount of time

[10] Bone conduction thresholds were obtained when there was more than a 20dapa pressure measurement during immittance to rule our any even minimal active middle ear involvement.

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required for data analysis, three-rater comparisons are not considered. From a time efficiency viewpoint, the Mf ASSEP shows dramatic advantages over time ABR protocol. The time efficiency is again addressed in the impaired ears to assess the influence of impairment on the duration of the protocols.

In the experimental group:

- The average pure tone audiogram in the experimental group took **20 minutes**
- The average Mf ASSEP procedure took **28 minutes (SD 11)**
- The average ABR click and tone burst protocol took **24 minutes (SD 9).**

The subjects were co-operative and well acquainted with the testing procedure. Co-operation was optimal and all pure tone results can be deemed reliable. No aided thresholds were obtained.

Although the ABR protocol took marginally less time to complete, it only provided a threshold estimate at one frequency, with an additional high frequency point based on the transducer used. In order to achieve the same results as with the Mf ASSEP technique, the time it took to obtain a threshold using tone burst at 500 Hz should be quadrupled for four comparative frequency points, and then doubled to obtain thresholds in both ears. The waveform analysis for the ABR test was also not included in the calculation.[11]

Time efficiency remains a contentious issue in clinical practice. Evoked potential testing is particularly plagued by the void between excellent correlations in research papers and

[11] Subject preparation and electrode placement were not considered in the time calculation. The time was recorded for the physical obtaining of thresholds once the subjects were prepared, impedance checked and the test environment stabilized.

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the challenge of diagnosing actual patients with potential hearing loss using these methods. It is encouraging to see that Mf ASSEP could elicit the same amount of information with reasonable accuracy in approximately 10 minutes longer than it took to complete a behavioral pure tone audiogram.

Although this is an important comparison, it defeats, in one sense, the purpose of an evoked potential test procedure, which is the substitution of unreliable or incomplete behavioral thresholds for whatever reason. The comparison between the two electrophysiological test batteries is, therefore, more weighted, as they would be on a level playing field when options exist in difficult-to-test populations. Mf ASSEP proved to be the most time efficient in providing eight frequency specific threshold estimates, with the additional benefit of double objectivity (i.e. the patient is not required to respond and the tester is not required to analyze data to determine the nearest to threshold recognizable response) when compared to the ABR protocol. Even though the ABR procedures took four minutes less in to complete in comparison, the actual analyses of waveforms were not included. The ABR protocol was also limited in its provision of frequency specific threshold estimates across the frequency range.

The time efficiency parameters concluded the whole group description of the data. Additional to the accuracy considerations, the preceding description of the normal and whole group data afforded a macroscopic view of the entire empirical component of the study. The next section will provide a mesoscopic view within the impaired group, as the manipulations in the degree and configuration of hearing loss will be discussed.

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5.5 RESULTS OBTAINED IN EXPERIMENTAL GROUP USING DEGREE OF HEARING LOSS AS PRIMARY PARAMETER

Once it has been established that the audibility of a signal has been reduced, the severity of hearing loss is delineated from the absolute pure tone thresholds, or in the case of special populations, the thresholds estimates gained from other procedures such as evoked potentials. This section describes degree of hearing loss or range of deafness within the confines of sensory-neural hearing loss.

The data distributed between the categories characterizing severity of hearing loss are presented in hierarchical fashion. The discussion commences with the tabulated version of the mean data per degree category. The presentation is then narrowed to difference in threshold, succeeded by graphic displays of the categories in audiometric format.

Table 5.9 Mean values of the hearing impaired group according to degree across the frequency range

CLASSIFICATION BY DEGREE	MEAN VALUES OBTAINED IN EACH TEST PROCEDURE IN dB HL									
	Pure tone threshold				Minimal response level Mf ASSEP				ABR Tone burst at 0.5 kHz	ABR Click 1-4 kHz[12]
	0.5	1	2	4	0.5	1	2	4		
Normal	14	15	14	29	40	43	40	58	50	50
Mild	24	31	39	45	49	50	59	56	58	43
Moderate	39	42	57	58	54	69	70	71	61	68
Moderate-severe	34	51	75	74	43	78	85	88	57	84
Severe	73	84	86	85	100	90	110	90	84	85
Profound	81	94	103	111	100	110	90	110	95	94

[12] Estimated frequency range for transient broadband click stimulus with supra-aural headphone transducers

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From Table 5.9, it is clear that the general tendency is towards a gradual increase in threshold as the categories progress. It is interesting to note that in the moderate-severe category, the data points at 0.5 kHz fall *below* the moderate category in all testing conditions (i.e. have better threshold in the "worse" category). Three explanations can be provided. This could firstly be attributed to the incomplete elimination of the influence of the configuration in the classification of hearing loss. Secondly, in the calculation of the pure tone average, which was employed to determine the degree categories, a modification was made to include 4 kHz. This modification furthermore influenced the mean values. Thirdly, the unequal distribution of subjects across the severity categories also contributed to the discrepancy evident between the moderate and moderate severe categories.

The degree categories containing the mean values do not, however, illuminate the exact nature of the correlation between the three test protocols in a satisfactory manner. A closer inspection of this relationship may be obtained by the calculation of the *difference in threshold* between the various test conditions at comparative points. The differences are tabulated in Table 5.10.

Table 5.10 Difference in minimum response levels in three test protocols

Difference in threshold measured in dB HL					
	Degree of hearing loss (Northern & Downs, 1991)				
Pure tone and Mf ASSEP	Mild (26-40 dB	Moderate (41-55 dB)	Moderate – Severe (56-70 dB)	Severe (71-90 dB)	Profound (91+ dB)
0.5 kHz	25	15	9	27	19
1.0 kHz	21	27	27	6	16
2.0 kHz	20	13	10	24	-13
4.0 kHz	11	13	14	5	1
Pure tone and ABR with tone burst at 0.5 kHz	34	22	23	11	14
Pure tone at 2kHz and ABR click	4	11	9	1	-9
Pure tone at 4 kHz and ABR click	-2	10	10	0	-17

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The difference between pure tone thresholds and the Mf ASSEP minimal responses showed 20% of the response within 10 dB of each other. Forty percent of the responses were within 20 dB of the pure tone thresholds and 35% were within 30 dB of the pure tone threshold. In one instance (5%) the responses showed an overestimation of the pure tone threshold in the profound range at 2 kHz. At very high intensities this discrepancy could have been either a vibro-tactile threshold recording during pure tone audiometry or it could have been the effect of recruitment and high stimulus intensities through the earphones during Mf ASSEP recording. The influence on management and selection of amplification in the 91+dB hearing loss range is not as significant.

The picture is amplified even further when each category is presented separately. The use of an audiogram format is employed to present the data graphically.

5.5.1 Mild hearing loss

Eight ears were examined in this category. The results are displayed in Figure 5.6.

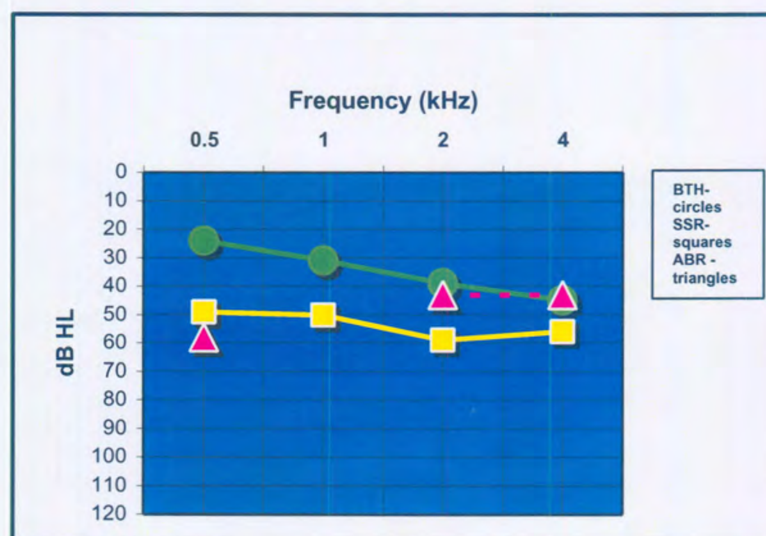

Figure 5.6 Display of ears with MILD hearing loss

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The difference between pure tone thresholds and the Mf ASSEP minimal responses showed 20% of the response within 10 dB of each other. Forty percent of the responses were within 20 dB of the pure tone thresholds and 35% were within 30 dB of the pure tone threshold. In one instance (5%) the responses showed an overestimation of the pure tone threshold in the profound range at 2 kHz. At very high intensities this discrepancy could have been either a vibro-tactile threshold recording during pure tone audiometry or it could have been the effect of recruitment and high stimulus intensities through the earphones during Mf ASSEP recording. The influence on management and selection of amplification in the 91+dB hearing loss range is not as significant.

The picture is amplified even further when each category is presented separately. The use of an audiogram format is employed to present the data graphically.

5.5.1 Mild hearing loss

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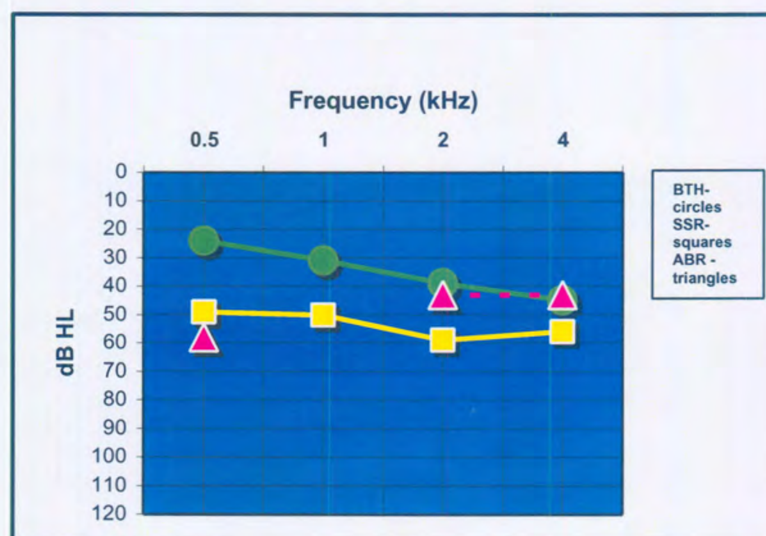

Figure 5.6 Display of ears with MILD hearing loss

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As expected, the broadband click enabled the closest approximation to pure tones in the higher frequency regions. The nature of the click stimuli and the frequency shaping by the air conduction transducers, such as head phones, cause relatively flat amplitude spectra and flat frequency responses respectively (Gorga, Kaminski, Beauchaine & Bergman, 1993). While the advantages of increased neural synchrony (and thus clearer wave morphology and larger amplitude) decreases the threshold of audibility, especially in the mid frequency region (1-4 kHz), the threshold of audibility becomes progressively poorer for higher and lower frequencies, producing a response that limits independent frequency information (Gorga et al., 1993).

The Mf ASSEP results provide overall accuracy in predicting pure tones, with poorer correlation than click ABR, yet with the continued maintenance of frequency specificity. Compared to the alternative in frequency specific hearing prediction of tone burst ABR, better correlation to pure tones was evident. Mf ASSEP thresholds were on average 20 dB poorer than the pure tone thresholds, with the difference decreasing at 4 kHz. The Mf ASSEP results can therefore be implemented as a core definitive procedure in the categorization of mild hearing loss across frequencies. This finding is in keeping with the data collected by Lins & Picton (1995), Lins et al. (1996) and John et al. (1998) using a multiple technique.

The poorest correlation was evident between the pure tone results at 0.5 kHz and the tone burst ABR. A minimal response was evident at 60 dB HL, but when the correction factor (30 dB) (Hall & Mueller, 1997) is introduced, threshold is estimated at within 5 dB of the pure tone. The poorer wave morphology, longer latencies and smaller amplitudes when compared to the click ABR (Hall, 1992; Hood, 1998) are however current and ongoing clinical concerns.

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5.5.2 Moderate hearing loss

Nine ears were examined in this category. The results are displayed in Figure 5.7.

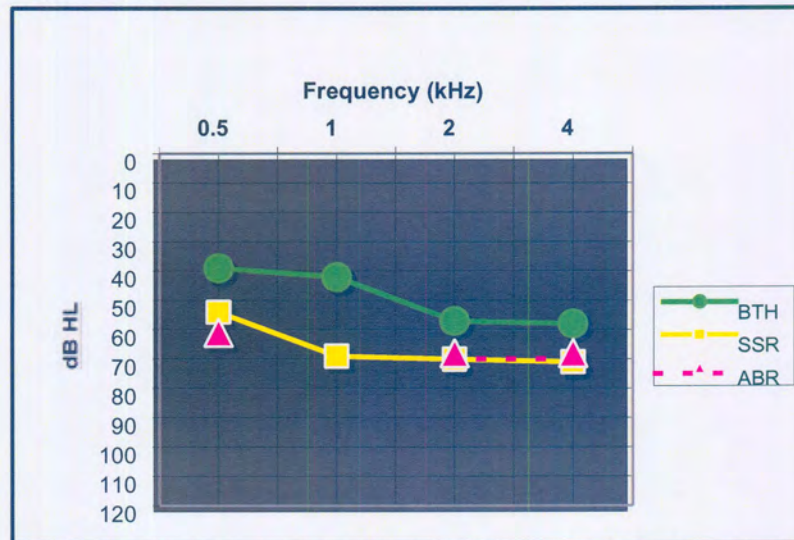

Figure 5.7 Display of ears with MODERATE hearing loss

No discrepancies were evident in this category. The best approximation of pure tone data was attained by Mf ASSEP that were 24, 27, 23 and 13 dB poorer than the pure tone thresholds at 0.5, 1,2 and 4 kHz respectively. Click ABR proved to equally sensitive to the degree of hearing loss in the higher frequencies with equal minimal response levels equal to the Mf ASSEP, yet lacking frequency specific information. Tone burst ABR revealed the poorest approximation of the pure tone threshold in the 0.5 kHz region.

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5.5.3 Moderate-Severe hearing loss

Four ears were examined in this category and the results are displayed in Figure 5.8.

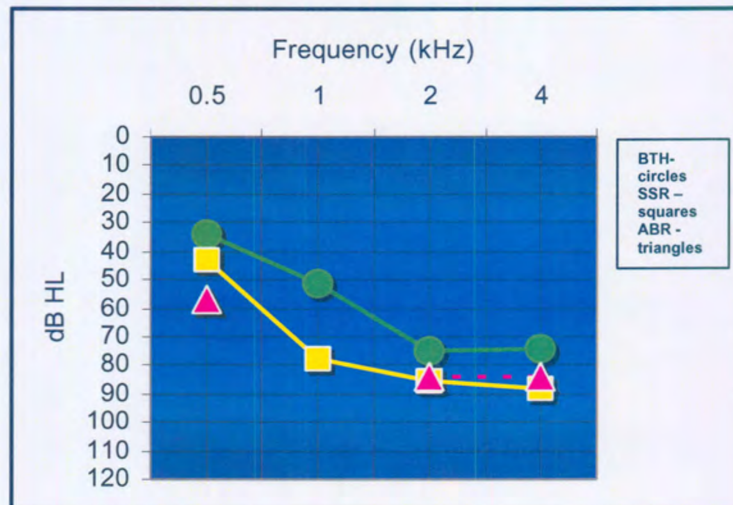

Figure 5.8 Display of ears with MODERATE –SEVERE hearing loss

The smaller number of ears weakens the comparative value in this category. The Mf ASSEP exhibited the closest approximation to pure tone levels in the low frequency region (9dB difference between Mf ASSEP and pure tone). The high frequency region was represented with equal levels of accuracy, with the distinction of frequency separation provided by Mf ASSEP and not by the click ABR. Furthermore, while it was not formally explored, the Mf ASSEP also imitated the curve of the pure tone audiogram across the frequency range.

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5.5.4 Severe hearing loss

Fourteen ears were examined in this category. The results are displayed in Figure 5.9.

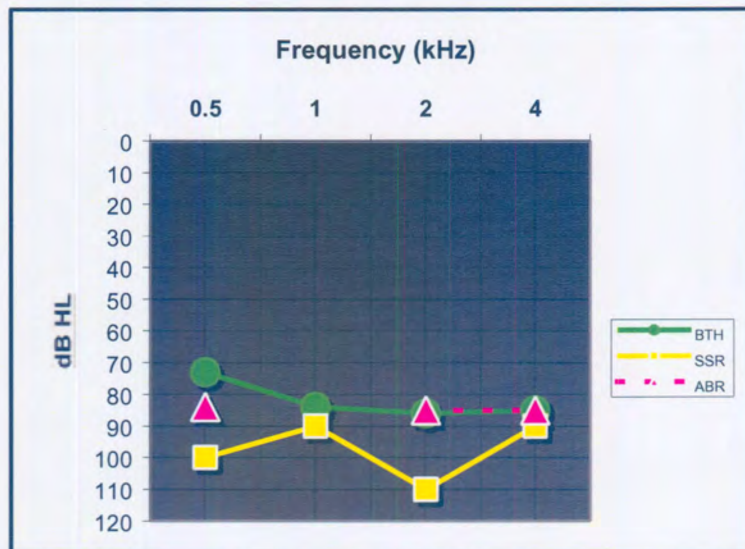

Figure 5.9 Display of ears with SEVERE hearing loss

The closest approximation of pure tone data was obtained for the ABR test protocols. The tone burst ABR at 0.5 kHz predicted the degree of hearing loss to within 5 dB of the pure tone threshold, the best correlation of all the tone burst results across the degree categories. The click ABR minimum response levels were identical to the pure tone. This should, however, not create a false sense of security. The introduction of correction factors (Hall & Mueller, 1997) that decreases the estimate level into closer approximation to the pure tone may cause the underestimation of pure tone threshold in the clinical setting. The use of a test battery and the inclusion of speech measurements, acoustic reflexes and comprehensive case history should assist in this regard.

Mf ASSEP results were able to predict a severe hearing loss, yet the data points exhibited a seesaw pattern not evident in the pure tone data. The difference between

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pure tone and Mf ASSEP data points at the four frequencies ranged from 27 dB, shrinking to 6 dB, extending to 24 dB, then shrinking back to 5 dB. The differences did not, however, extend outside of the severe hearing loss range.

5.5.5 Profound hearing loss

Ten ears were examined with a profound hearing loss (>91 dB HL).

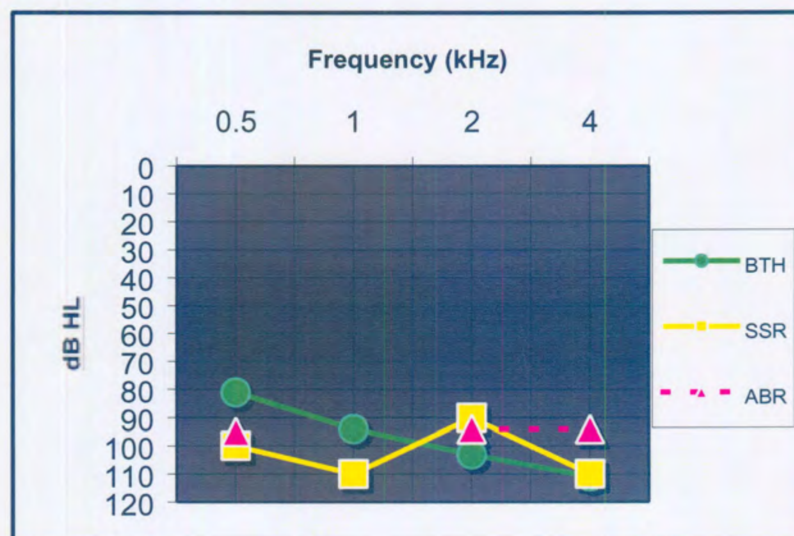

Figure 5.10 Display of ears with PROFOUND hearing loss

The high frequency results at 2 and 4 kHz showed that the evoked potentials had better minimal responses than the pure tone thresholds at these frequencies, not evident in the low frequencies. As with most testing procedures in this particular range of deafness, this may be the result of high intensity levels required to obtain responses. The data suggest that the possibility of tactile thresholds at high intensities cannot be ruled out.

The three displays of degree data (means, differences and audiograms) seem to illustrate the ability of the Mf ASSEP and the ABR protocol to predict the degree of

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hearing loss accurately. These tendencies were examined statistically. The findings are tabulated in Table 5.11.

Table 5.11 Effect of degree on SS test accuracy

Test procedure	Pure tone threshold				Mf ASSEP MRL				ABR tone burst	ABR Click
Frequency in kHz	0.5 kHz	1.0 kHz	2.0 kHz	4.0 kHz	0.5 kHz	1.0 kHz	2.0 kHz	4.0 kHz	0.5 kHz	1-4
P level	.0000	.0000	.0000	.001	.0011	.0001	.0002	.0362	.0032	.0030
Significance ($p<0.01$)	Significant	Significant	Significant	Significant	Significant	Significant	Significant	Reaches significance at $p<0.03$	Significant	Significant

The data indicate that both evoked potential protocols have a high sensitivity to variations in severity of hearing loss. Therefore, hearing acuity may be accurately portrayed across the degree spectrum from normal and mild to profound hearing loss. The Mf ASSEP at 4.0 kHz obtained slightly less significance.

5.6 RESULTS OBTAINED IN THE EXPERIMENTAL GROUP USING CONFIGURATION OF HEARING LOSS AS PRIMARY PARAMETER

Adhering to the general protocol in diagnostic audiometry, which describes the degree of hearing loss followed by the ear involved, the next introduction is usually a descriptive term to indicate the configuration of the hearing loss (Roeser at al., 2000a). As was the case for degree of hearing loss, three methods of display will be employed. The mean data of each configuration category will be presented, followed by the differences in minimal response levels. The effect of the configuration will then be illustrated, followed by graphic displays of the categories in audiogram format.

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The mean values of the three test protocols are presented in Table 5.12 as a reference for the configuration results.

Table 5.12 The mean values obtained in each category of the configuration categories

CONFIGU-RATION	VALUES OBTAINED IN EACH TEST PROCEDURE									
	Pure tone threshold				Minimum Response levels Mf ASSEP				ABR Tone burst at 0.5 kHz	ABR Click 1-4 kHz[13]
	0.5	1	2	4	0.5	1	2	4		
Flat	36	38	34	37	62	57	58	55	68	44
Gradual slope	33	49	63	61	45	83	75	78	59	75
Ski-slope	25	28	53	71	50	56	68	99	63	79
Low Frequency	80	80	65	55	45	55	60	45	75	65
Notch	50	70	70	75	30	40	70	50	70	75
High Frequency	23	28	46	58	38	50	58	60	58	61

Because of the nature of the allocation, clear trends are not as easily observed as with the gradual increases in the degree classification. However, one important trend could be observed. The evoked potential protocols were generally at higher intensity levels than the pure tone thresholds for most of the configurations. Two exceptions need to be highlighted at this early juncture. In the low frequency category, the Mf ASSEP minimal response levels were better than the pure tones across frequency points. In the notch category, the same could be observed. These two findings will be elaborated upon extensively throughout the course of the chapter. To illuminate the extent of the overestimation of pure tone thresholds in these categories and also to highlight the performance of the evoked potential protocols in the other categories, the differences between response levels at similar reference points are presented below in decibel HL.

[13] Estimated frequency range for transient broadband click stimulus with supra-aural headphone transducers

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Table 5.13 Difference in minimal response levels in three test protocols.

Difference in threshold measured in dB HL						
	Configuration of hearing loss (from Roeser et al., 2000a)					
Pure tone and Mf ASSEP	Flat	Gradual slope	Ski slope	High frequency	Notch	Low frequency
0.5 kHz	26	12	25	15	-20	-35
1.0 kHz	19	34	28	22	-30	-24
2.0 kHz	24	12	15	12	0	-5
4.0 kHz	18	17	28	2	-25	-10
Pure tone and ABR with tone burst at 0.5 kHz	32	26	38	35	25	-5
Pure tone at 2kHz and ABR click	10	12	26	15	5	0
Pure tone at 4 kHz and ABR click	7	14	-15	3	0	10

The Mf ASSEP showed a different distribution pattern from the degree classification. A higher occurrence of underestimation of threshold was evident in Mf ASSEP and the breakdown is as follows: Mf ASSEP showed the highest percentage of 33% within 20 dB of the pure tone threshold (eight data points indicated in blue). Eight (29%) of the minimal response levels were underestimations of the threshold (indicated in gray grid). 25 % of minimum response levels (six data points indicated in red) were within 30 dB of the pure tone results. Only 8 % (two data points indicated in green) of the Mf ASSEP was within 10 dB of the pure tones. Four percent of the results (one instance), the Mf ASSEP was within 40 dB of the pure tone result.

Tone burst ABR response levels showed all of the results to be within 40 dB of the pure tone, with 33% (2 data points in red) being within 30 dB of the pure tones. Sixteen percent of the results (one instance) was an underestimation of the pure tone results.

The click ABR showed poorer correlation with the pure tone at 0.2 kHz than 0.4 kHz. Sixteen percent of the ABR click results were within 30 dB of the pure tone at 2.0 (one data point indicated in red), none showed that correlation with 4.0 kHz. One instance (33%) of the ABR click results were within 20 dB of the pure tone at 2.0 (indicated in

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blue) with 16% of the results being within 20 dB of the pure tone at 4.0 kHz. 50% of the results were within 10 dB (indicated in green) of the pure tone at 2.0 kHz, but 66 % of the ABR were within 10 dB at 4.0 kHz. One instance (16%) of underestimation occurred with click ABR at 4.0 kHz in the ski-slope category.

Despite the large quantity of underestimation evident in two categories, there was no significant effect of configuration with statistical analyses on the accuracy of Mf ASSEP as a result of the small sample of subjects in the underestimated categories. The p-levels are displayed in Table 5.14.

Table 5. 14 Effect of configuration

TEST PROCEDURE	PURE TONE THRESHOLD				MINIMUM RESPONSE LEVELS MF ASSEP				ABR TONE BURST	ABR CLICK
Frequency in kHz	0.5	1.0	2.0	4.0	0.5	1.0	2.0	4.0	0.5	1-4
P level	.0984	.0980	.4800	.1581	.0632	.1056	.2315	.0318	.2752	.7800
Significant at 0.01	X	X	X	X	X	X	X	X	X	X

The effect analysis determined that, irrespective of the degree of hearing loss, Mf ASSEP could predict the severity of the hearing loss. As each of the degree categories was separated and the minimum response levels correlated to the pure tone audiogram, a similar procedure was followed with the configuration categories, particularly in the light of the discrepancies in two of the categories. The results are presented in Figure 5.11.

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5.6.1 Flat configuration

Smaller than 20 dB variation between 0.5 kHz and 4.0 kHz

Eighteen ears were examined in this category.

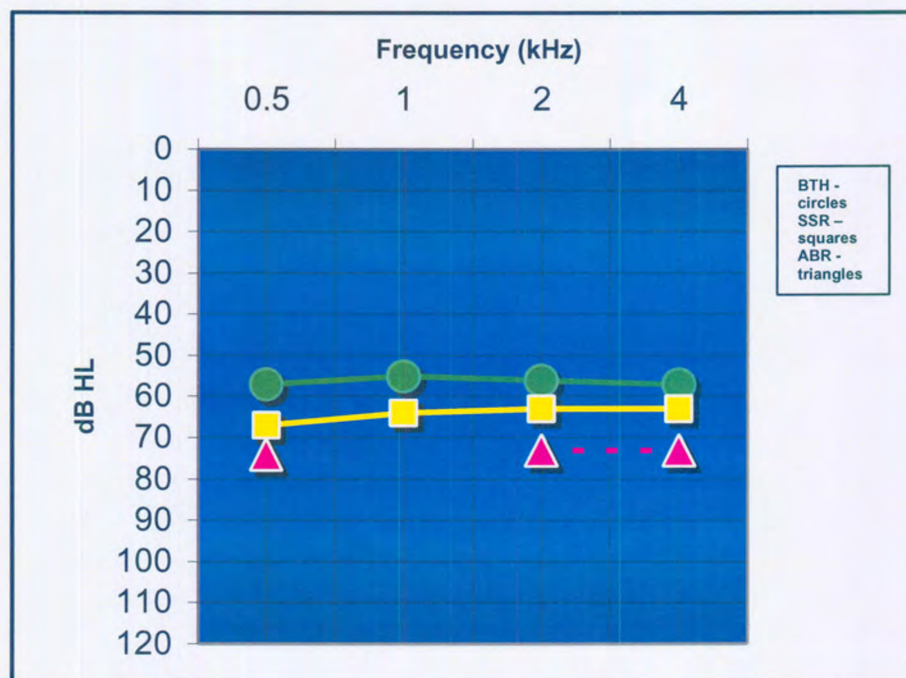

Figure 5.11 Display of ears with a flat audiogram configuration

Mf ASSEP response levels were within 10 dB of the tone thresholds and the respective differences were 10,9,7 and 6 dB respectively for 0.5,1,2,and 4 kHz. ABR results followed a similar pattern, but the difference between ABR and pure tone levels was 32 dB larger at 0.5 kHz, and 10 and 7 dB at 2 and 4 kHz respectively. The click ABR showed no frequency specificity outside the high frequency region. Both protocols would have served adequately to predict hearing status for amplification purposes. The increased frequency specificity across the frequency spectrum, combined with automatic response detection and subsequent elimination of human error, as well as the significant

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reduction in testing time, favors the use of Mf ASSEP in the prediction of hearing in this particular category.

5.6.2 Gradual slope

Pure tone thresholds increase gradually as frequency increases

Eleven ears were examined in this category.

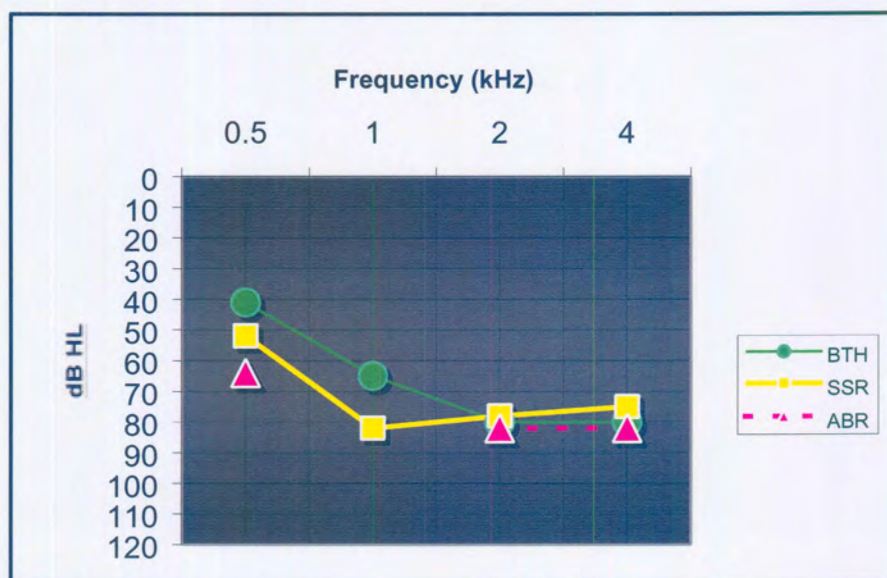

Figure 5.12 Display of ears with a gradual slope audiogram configuration

Low frequency information showed Mf ASSEP to be within 9 dB of the pure tone threshold at 0.5 kHz when compared to the poorer tone burst point, which showed a 23-dB difference from the same 0.5 kHz pure tone. The Mf ASSEP seemed to be a more accurate predictor of threshold than the tone burst. The Mf ASSEP minimum response levels were almost identical to the pure tones at 2.0 and 4.0 kHz (Mf ASSEP was better by 2 dB). The 2dB discrepancy is insignificant in this particular case, as it would not affect the selection of amplification or the management of this particular case in any way. Large responses near threshold level in pathological ears have been documented by

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Picton et al. (1998) and are ascribed to recruitment. The interaction of multiple stimuli at high intensities has not been clarified to date, but it seems that in this particular category there was no hindrance in accuracy when the configuration was manipulated. The click ABR showed an accurate estimation of the 2-4 kHz region.

5.6.3 Ski slope

Flat configuration up to 1 kHz with > 15 dB PTT decrease in the high frequencies.

Eight ears were examined in this category.

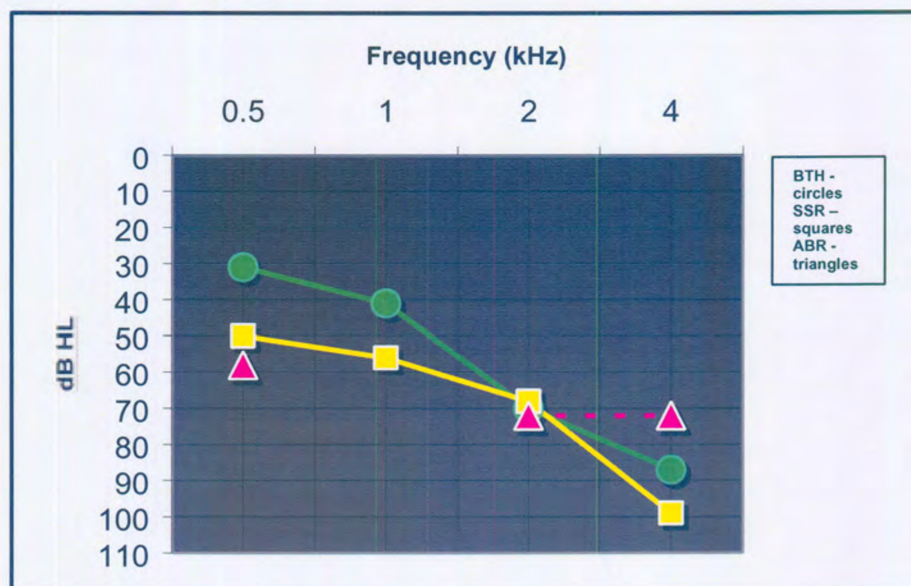

Figure 5.13 Display of ears with a ski slope audiogram configuration

Low frequency findings indicated a 19 dB difference between pure tones and Mf ASSEP compared to the 27 dB difference between pure tone and tone burst at 0.5 kHz. The high frequency findings showed better correlation than the low frequencies with Mf ASSEP with a 2dB difference at 2.0 kHz and a 12dB difference at 5.0 kHz when compared to pure tones. It was, furthermore, encouraging to observe the Mf ASSEP imitation of the pure tone configuration's sharp slope with 31 and 41 dB at 0.5 and 1.0

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kHz sharply increasing to 70 and 87 dB in the pure tones and 50 and 56 at 0.5 and 1.0 kHz and 68 and 99 dB at 2 and 4 kHz with Mf ASSEP.

The transient nature of the click stimulus of the ABR did not articulate into minimum response levels that accommodated the configuration, possibly reacting to the better hearing at 1.0 kHz while being insensitive to the 4 kHz decrease in sensitivity evident in the pure tones and Mf ASSEP results. This caused a significant underestimation of threshold in the high frequencies, which may be a critical oversight in providing adequate access to speech information by amplification of residual hearing. A possible consequence of this underestimation related to the accountable management of this case. A threshold at 90 dB in the high frequency region may well lead to exploration into the feasibility of cochlear implantation, while a threshold at 70 dB does not immediately create this management option. Although the low frequencies are exceptionally good, and therefore contra-indicative of cochlear implantation at the onset of management, the use of frequency specific tone burst at all key frequencies in determining more accurate high frequency hearing levels is clearly indicated by this finding.

5.6.4 High frequency

Normal hearing up to 2 kHz with a decrease from 3 kHz onwards.

Only a small sample of four ears was included in this category.

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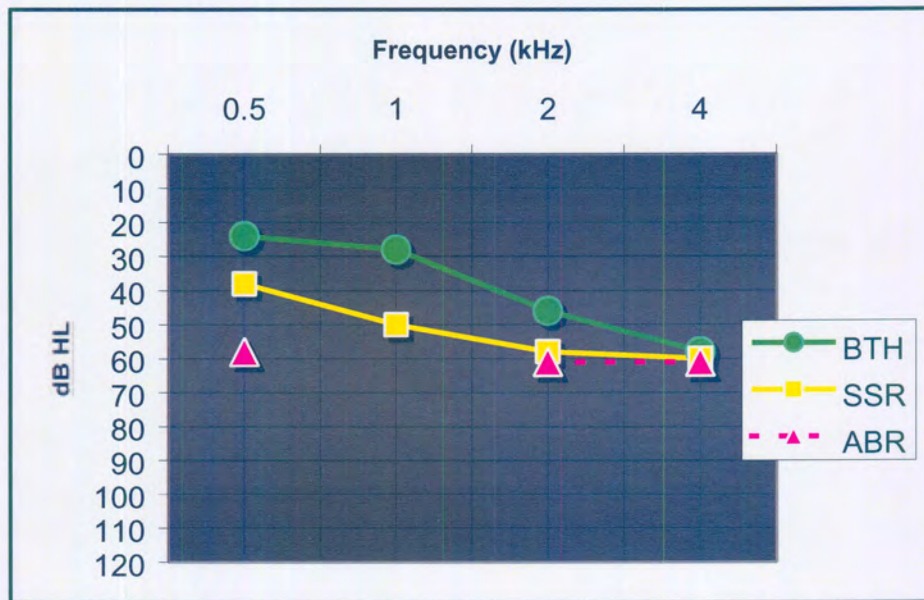

Figure 5.14 Display of ears with a high frequency audiogram configuration

No discrepancies were observed with either evoked potential technique. The Mf ASSEP protocol rendered low frequency response levels in closer approximation to the tone burst ABR at 0.5 kHz. The Mf ASSEP imitated the high frequency configuration closely, which is encouraging, as there is a high incidence of high frequency hearing loss. The intensity levels did not, however, exceed moderate levels (60-70 dB), and the influence of exceedingly high intensity levels on the threshold estimated with the Mf ASSEP technique was not explored.

5.6.5 Notch

Notch shaped loss (also inverse notch) around 1 – 3 kHz

This category suffered from a limited data set of four ears and one of the cases presented with an inverse notch.

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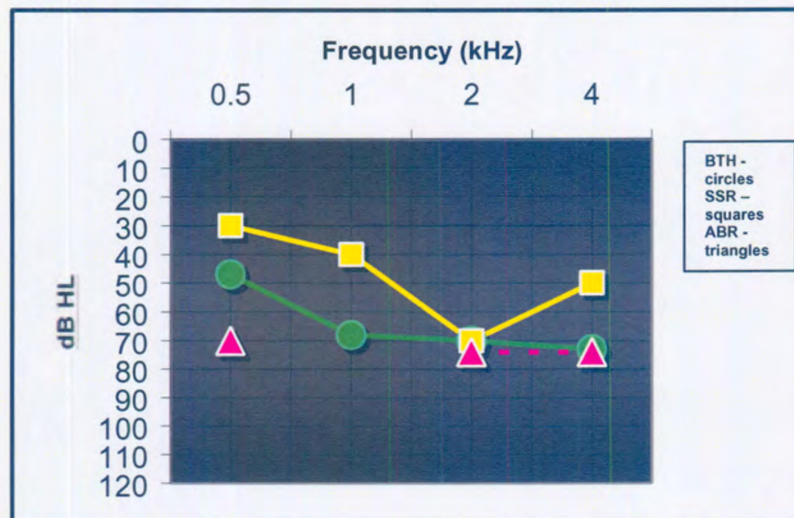

Figure 5.15 Display of ears with a notch shaped audiogram configuration

The notch category, with its inherent flaws of limited data and one inverse configuration, showed significant discrepancies in test protocols. The Mf ASSEP responses were significant underestimations of low frequency hearing (0.5 and 1.0 kHz) as well as at 4.0 kHz even though intensity levels did not exceed moderate levels. The ABR protocol did not underestimate threshold in the low or high frequency range but was insensitive to the specific configuration pattern. The inaccurate cases will be examined individually in the concluding section of the chapter.

5.6.6 Low frequency

0.5 and 1 kHz more involved than 2.0 and 4.0 kHz

Six ears were examined in this category.

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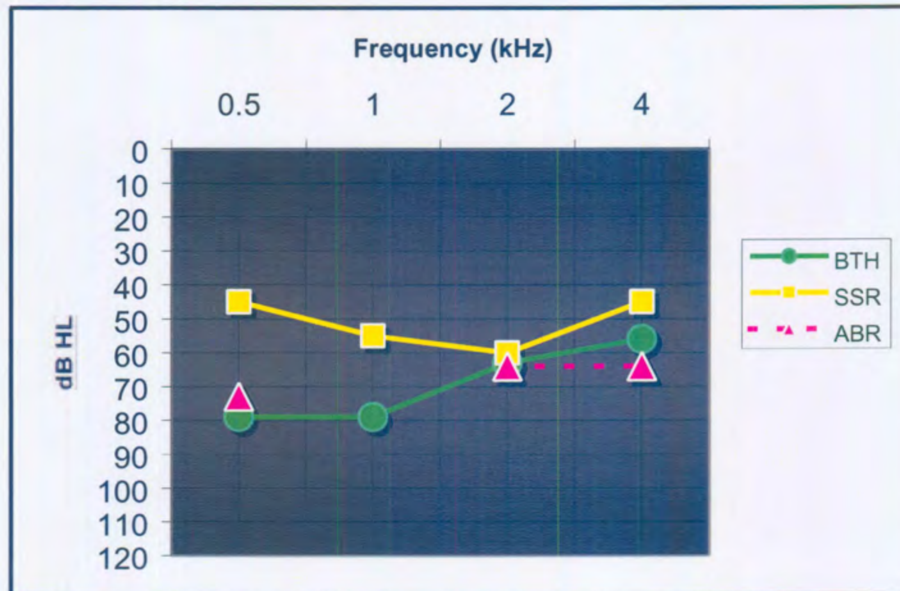

Figure 5.16 Display of ears with a low frequency audiogram configuration

Sensorineural etiologies producing low frequency hearing loss are less common (Hall, 1992:348). Most low frequency hearing loss is reflective of conductive hearing loss usually associated with middle ear pathology, or with mixed heating loss due to a pathology that may involve the middle and inner ear such as otosclerosis (Hall, 1992). The small number of subjects in this category is indicative of the relatively small number of people with low frequency sensorineural hearing loss. The small number unfortunately precludes quantitative judgment but it is apparent that the low frequencies showed significant overestimation of hearing sensitivity with Mf ASSEP. Although the 4.0 kHz Mf ASSEP was also an overestimation, it was not as significant as the low frequency threshold predictions. The tone burst ABR also showed an overestimation of 6 dB but it was not as severe as with Mf ASSEP. The pure tone thresholds were at higher intensity levels than in the notch category where inaccurate predictions occurred. The influence of intensity can, therefore, not be ruled out in the low frequency category. It may be concluded form the three sets of data (central tendencies, correlation and audiogram

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displays) that the use of Mf ASSEP is not adversely affected by manipulation of audiogram configuration across the frequency range.

5.7 INDIVIDUAL CASES WHERE Mf ASSEP THRESHOLD ESTIMATES DID NOT ACCURATELY TRANSLATE INTO PURE TONE THRESHOLDS

The previous sections indicated that the degree of hearing loss had a significant effect on the MRLs with Mf ASSEP as well as the ABR protocol. Stated clinically, the Mf ASSSEP seemed able to predict hearing loss irrespective of the severity, hence its suitability across the range of deafness.

Furthermore, configuration of hearing loss showed no effect on the MRLs obtained with the Mf ASSEP and ABR. Within the clinical paradigm, these findings articulate into test procedures that are able to accommodate the various audiogram shapes without limiting the accuracy of the pure tone estimation. Some of the aggregate audiograms of the configuration categories, however, seemed to indicate something different. It was particularly in the low frequency and notch configurations where clearly evident overestimations of pure tone thresholds were present. While these findings were not statistically significant, each will be examined to seek answers to why threshold prediction was inaccurate.

The rationale for this analysis is based on the words of one of the pioneers in the field of audiology and a recipient of the Nobel prize for Physiology and Medicine, Georg von Békesy: *"One of the most important features of scientific research is the detection of errors. The writer believes that positive results and failures should be discussed together. Only by such complete reporting can we get a true conception of a piece of work, of the manner of its development, and of the limitations of its principles" (1960:7).*

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The general concern in each category and the major impact on the findings, was the **limited number of subjects**, as already mentioned. While the obvious recommendation would be to seek out more participants in each category, these configurations of loss are uncommon in sensory-neural hearing loss (Hall, 1992). The limited number of subjects was, therefore, disappointing and even frustrating, but not surprising, even in this data set.

Another critical contributor to these inaccurate estimations had to do with the **severity of the hearing loss** that caused statistical error. The severe to profound hearing losses in the two configuration categories often showed no response at maximum level of stimulus, and these findings were not added to the sum for statistical analysis. This limits the data set to fewer numbers than even the number of ears already present, therefore skewing the results even further. It was only closer inspection of each audiogram in each of the two configuration categories that revealed three cases of true discrepancy. These three cases will be discussed separately.

5.7.1 Findings of the notch configuration

Definition: notch shaped loss (also inverse notch) between 1 – 3 Khz

Number of ears: 4

In the notch category, two cases showed discrepancy. The accurate findings are tabulated below, followed by audiograms with the inaccurate predictions.

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Table 5.15 Accurate findings in the notch configuration

NOTCH											
CASE	EAR	Pure tone thresholds in dB				Mf ASSEP in dB				ABR	ABR
		0.5	1	2	4	0.5	1	2	4	Tone Burst at 0.5Hz in dB	Click in dB
1	LEFT	80	85	70	105	90	100	80	NR	NR	75
2	LEFT	40	95	90	80	80	100	NR	NR	80	85
3	LEFT	15	25	50	35	30	40	70	50	30	40

From Table 5.15 it is clear that some of the evoked potential was absent as a result of the severity of the hearing loss:

- Case 1 showed no response with Mf ASSEP at 4 kHz and ABR with tone burst (0.5 kHz).
- In Case 2 hearing estimation was accurate, but the intensity levels of the stimulus in the multiple stimulation mode precluded the behavioral envelope of the configuration to be followed by the Steady State results.
- An accurate prediction of degree and configuration of hearing loss is evident in Case 3. The lesser severity of the hearing loss, (i.e. a complete data set for each testing condition) may have been the contributing factor in accurately predicting this rather unusual hearing loss. It is interesting to note that the tone burst data was identical to the Steady State data, but that the click, with its lack of frequency specificity, underestimated the hearing loss in the 4 kHz region slightly. The inaccurate prediction is displayed in Figure 5.17.

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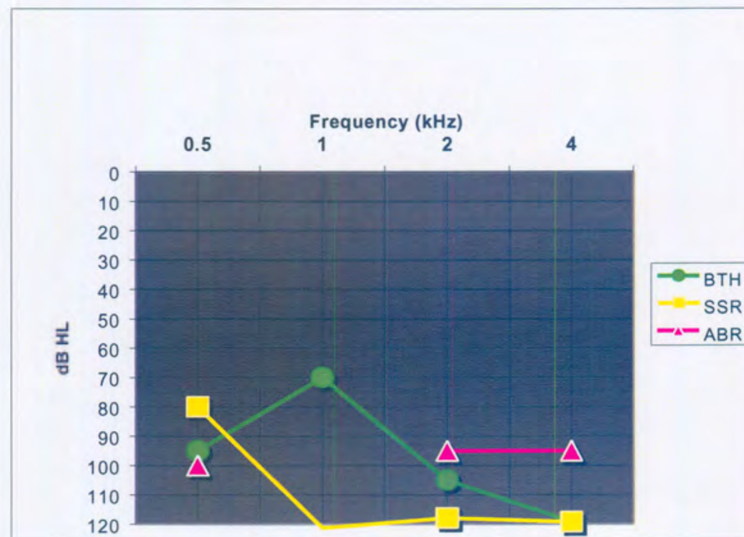

Figure 5.17 Audiogram of inaccurate prediction of threshold in the right ear of a female subject in the notch category

In this display, the Mf ASSEP underestimated the pure tone at 0.5 kHz by 15 dB. Click ABR underestimated the high frequency region, reacting to the better hearing at 1 kHz.

Two of the critical variables of the study, namely degree and configuration, come into play in this case. The contribution of each was, however, not equal. While the severity of the hearing loss complicated the distinction between auditory and vibro-tactile responses, the main contributor to the inaccuracy may have been the unusual configuration of the hearing loss.

In terms of the clinical outcomes, the results remained within the profound category, which means that the hearing aid selection in terms of maximum output, or the possibility of a cochlear implant, would not have been unduly compromised. The peak at 1 kHz may have been more complicated to address, and the use of tone hooks, ear mould modifications and circuitry to ensure comfort with increased speech intelligibility would have been explored.

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5.7.2 Findings in the low frequency configuration

Definition: 0.5 kHz more impaired than 2-4 KHz

Number of ears: 6

Table 5.16 Accurate findings in the low frequency configuration

LOW FREQUENCY											
CASE	EAR	Pure tone thresholds in dB				Mf ASSEP in dB				ABR	ABR
		0.5	1	2	4	0.5	1	2	4	Tone Burst at 0.5Hz in dB	Click in dB
1	Right	30	40	20	10	40	40	40	30	50	30
2	Right	85	85	75	65	95	NR	95	80	100	90
3	Right	110	110	95	100	110	NR	110	NR	NR	NR
4	Left	95	90	85	70	95	NR	NR	90	NR	90

Case 1 showed accurate prediction of threshold, with the Mf ASSEP and the ABR predicting the notch shape of the audiogram. The high correlation between the test protocols could have been enhanced in this particular audiogram by the mild degree of hearing loss.

Cases 2, 3 and 4 accurately showed that low frequencies were more affected by hearing loss than the high frequencies, but in Case 3 and 4 in particular the severity of the hearing loss precluded the presence of response levels across the entire frequency range of the electrophysiological test procedures.

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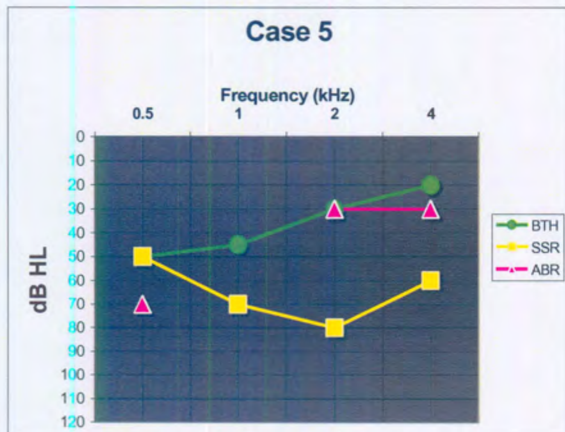

Figure 5.18 Overestimation

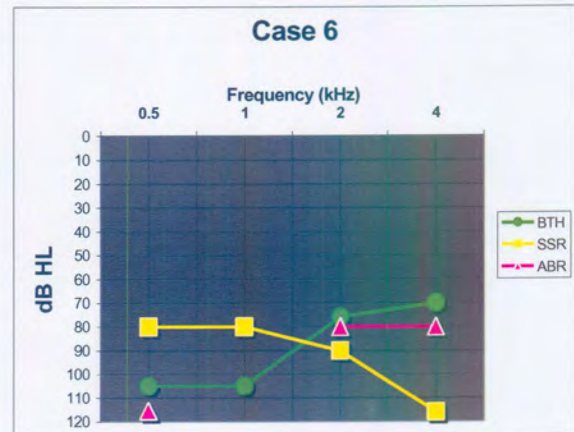

Figure 5.19 Underestimation

In each instance, the Mf ASSEP was inaccurate. In the first audiogram the Mf ASSEP overestimated 1, 2 and 4 kHz pure tone levels. In the second audiogram, the Mf ASSEP underestimated the low frequency pure tone levels. In both cases, the use of the ABR protocol rendered more diagnostically valid information in terms of amplification options.

In Case 5, degree of hearing loss could not have affected the Mf ASSEP adversely, as the pure tone thresholds fell in the moderate category. The unusual configuration of the hearing loss, however, could have negatively influenced the prediction of low frequency points.

Case 6 showed underestimation of the low frequencies. In this case, the degree of hearing loss may have contributed to the overestimation as the pure tone levels exceeded 90dB HL. The Mf ASSEP MRLs would not have affected the selection of amplification or cochlear candidacy.

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5.8 SUMMARY OF CHAPTER FIVE

The chapter has endeavored to give an account of the findings of the study. The account commenced with data obtained from normal ears using the three test protocols. The section was followed by presentation of the data from impaired ears. Data for the whole group were described, followed by a closer inspection of the degree and configuration categories within the group with impaired ears. The chapter concluded with a presentation of individual cases in which threshold prediction was inaccurate.

"The researcher's primary task in this sort of operation is: to illuminate 'taken-for-granted' meanings, to act as 'honest communicator' in opening up communication between different insider viewpoints; to clarify; to analyze; to act as 'honest broker' representing differences; to suggest ways of negotiating between them, and to make findings known" (Jan Waterson, 2001:141).

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CHAPTER SIX
DISCUSSION OF RESULTS

Aim of Chapter

The results of the study will be discussed to expound the significance and meaning within the framework of diagnostic audiological procedures.

6.1 INTRODUCTION

In this chapter, the results will be integrated and discussed. To arrive at this juncture in the proceedings, a comprehensive research plan was undertaken. In the preceding section, all results have been grouped and reported in an attempt to answer the research question posed in Chapter 1. The research question formed the basis of the formulation of aims (described in detail in Chapter 4), which provided the operational framework to obtain a body of knowledge (Smit, 1983). The realization of the sub aims identified relationships between variables to draw inferences, make predictions and provide comparative points across data as described in Chapter 5 (Smit, 1983).

The following section will deal with the interpretation, discussion and integration of the results to review their meaning and significance within existing literature and enable the formulation of a revised theoretical and clinical framework as tabulated in Table 6.1. *The researcher's primary task in this sort of operation is: to illuminate 'taken-for-granted' meanings, to act as 'honest communicator' 'in opening up communication between different insider viewpoints; to clarify; to analyze; to act as 'honest broker' representing differences; to suggest ways of negotiating between them, and to make findings known (Jan Waterson, 2001:141).* The discussion will commence with a summarized version (Table 6.1) of the study's results in relation to some other clinical findings in the literature.

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Table 6.1 Contribution of the current study within the context of existing literature on clinical application of the auditory steady state technique

Authors	SS Technique	Number of subjects	Hearing Status	Limitations	Findings of the current study
Rickards, Tan, Cohen, Wilson, Drew & Clark, 1994	Monotic	337 babies between 1 and 7 days old	Normal hearing	The procedure was limited in intensity level as it was performed for screening purposes.	No screening was attempted in the pediatric population
Rance, Rickards, Cohen, Burton & Clark (AUS), 1993	Monotic	25 children	Severe to profound hearing loss	The study concentrated on subjects with hearing loss in the severe to profound range.	This study was conducted across a full spectrum of degree and configuration parameters, however, not on children
Rance, Dowell, Rickards, Beer & Clark, 1998	Monotic	108	Severe-profound hearing loss	The study focused on subjects with severe to profound hearing loss.	
Johnson & Brown, 2001	Monotic	10 subjects	3 normal hearing 7 abnormal hearing	Limited number of subjects who were not representative of the various degrees and configurations of hearing loss	The current study utilized data obtained form 50 subjects with an equal distribution between normal and impairment
Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, Perez-Abalo, Martin & Savio, 1996	Dichotic	37	20 normal hearing adults 17 hearing impaired adolescents	The study was conducted at three different sites with different test protocols limiting comparative value The subjects were not representative of the various degrees or configurations of hearing loss	The current study was conducted at one site. Age and gender were controlled in the normal group and in the experimental group, the age range of the study was limited to adolescence
Perez-Abalo, Savio, Torres, Martin, Rodriguez, & Galan, 2001	Dichotic	83	43 hearing impaired children and 40 normally hearing adults	The spectrum of configuration of hearing loss was not represented and no consideration was given to age and gender effects that are well documented in the evoked potential literature	
Lins & Picton, 1995	Dichotic	40	Normal hearing	No data on the possible impact on an impaired	The normal data was verified and compared to the existing clinical findings, while the impact on an impaired system was explored
John & Picton, 2000	Dichotic	34			
John, Dimitrijevic & Picton, 2001	Dichotic	34			
Valdes, Savio, Sierra, Rodriques & Lins, 1997	Dichotic	16			
John, Lins, Boucher & Picton, 1998	Dichotic	16			
Herdman & Stapells, 2001	Dichotic and monotic	10			

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Within this context, the data obtained in the control and experimental groups will be discussed.

6.2 DISCUSSION OF FINDINGS OBTAINED IN THE GROUP WITH NORMAL HEARING

Findings in the normally hearing group indicated that the majority of Mf ASSEP MRLs (minimum response levels) fell within 40 dB across the 0.5 - 4 kHz frequency range with the highest percentage being within 35 dB of the pure tone levels. The tone burst ABR MRLs were also within 35 dB of the pure tone level at 0.5 kHz while the click ABR were within 20 dB of the pure tone levels at 2 and 4 kHz. These findings correlated with those described in the literature (Aoyagi et al., 1994; Lins et al., 1996, Picton et al., 1998; Perez-Abalo et al., 2001; Herdman & Stapells, 2001).

In the current study, however, some general findings with possible clinical significance were identified that should be addressed as research in this area continues. The use of normally hearing subjects affords researchers an opportunity to manipulate a variety of variables in order to achieve optimal testing conditions. Therefore, in an all-being-equal test paradigm, such as was attempted for the normally hearing group, the following issues require some discussion:

- Electrode placement
- Threshold seeking method

6.2.1 Electrode placement

Electrode placement of the reference electrode remains controversial. Picton et al. (1998) and John & Picton (2000) encourage the use of the nape of the neck because of clearer wave morphology (Hood, 1998, Hall, 2001, personal communication). Although

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this may be the case in a carefully controlled testing environment, such as a research laboratory, it is less than ideal in a clinical situation, which the current study tried to simulate. Abundant proof exists of increased artifact in the presence of neck and head movement and even tenseness on a electrophysiological measurement (Ferraro & Durrant, 1994; Weber, 1994; Hall & Mueller, 1997; Hood, 1998), motivating the use of sedatives in younger populations. No sedation was necessary, but the subjects were specifically encouraged to relax and even drowse while lying comfortably on their backs. Patient instructions included, as suggested in the literature, limiting movement of the neck, shoulders and eyes (Ferraro & Durrant, 1994; Weber, 1994; Hood, 1998; Wilson, 2000). Even though subjects were given deliberate instructions not to move, it was decided that the nape of the neck would be more susceptible to neck and head movement in the presence of tenseness. The current study, therefore, used the Oz position, which was reported to be slightly less comfortable by the research participants, as the electrode presses on the back of the head, but the use of a pillow for support eliminated discomfort to a large extent.

6.2.2 Threshold seeking procedure

A descending 10dB interval method was used during Mf ASSEP testing in the current study based on similar studies using identical equipment (Perez-Abalo et al. 2001) to facilitate comparison. The pure tone thresholds were, however, determined in 5 dB increments (Hall & Mueller, 1997). Within the context of the excellent hearing thresholds obtained in the current study, consideration should have been given to response detection in 5 dB increments in the Mf ASSEP protocol as well.

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6.3 DISCUSSION OF FINDINGS OBTAINED IN THE GROUP WITH IMPAIRED HEARING

The results obtained in the study indicated that degree of hearing loss had a marked effect on the MRL's of the study irrespective of the range while configuration showed little or no statistically significant effect on the accuracy of the MRL's in predicting the shape of the audiogram using either the Mf ASSEP protocol or the ABR protocol. The Mf ASSEP protocol, however, provided a complete four-frequency audiogram within an average time of 25 minutes in comparison to the ABR protocol, which provided a high frequency estimate and one low frequency threshold estimate. The findings seemed to lean towards a higher clinical utility for the Mf ASSEP protocol in terms of overall accuracy and time efficiency. Some discrepancy in the accuracy of each protocol was evident, however, and these findings and their clinical significance are expanded upon in Table 6.2.

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Table 6.2 Discrepancies between the test protocols

Category	Evoked Potential	Discrepancy	Clinical significance
Profound hearing loss	Click ABR	Underestimation of threshold at 2.0 with 5 dB and 15 dB at 4.0 kHz.	Not significant as the effect of vibro-tactile stimulation confounds true threshold by audition at high intensities (Hall, 1992). The effect of stimulus intensity is addressed under 6.3.2.2.4 Stimulus Intensity
	Mf ASSEP	Underestimated pure tine threshold with 10 dB at 2.0 kHz	
Gradual slope	Mf ASSEP	Underestimated pure tone threshold at 4.0 kHz with 5dB	Not significant as the underestimation falls within the standard deviations and does not affect amplification and other management options in this particular case.
Ski slope	Click ABR	Underestimated pure tone threshold with 15 dB at 4.0 kHz	Significant. Access to speech sounds is compromised in the frequencies critical for speech.
Notch	Mf ASSEP	• Underestimated pure tone at 0.5 kHz with 20 dB • Underestimated pure tone threshold at 1.0 with 30 dB • Underestimated pure tone threshold at 4.0 kHz with 20 dB	Significant. The threat of under-amplification in the low, mid and high frequency range would have been a very real possibility. This is, however, mean data of a very scantly compiled category and it is not a true reflection of the clinical effectiveness of the MF ASSEP.
Low frequency	Tone burst ABR	Underestimated pure tone threshold at 0.5 kHz with 5 dB	Not significant as the finding remains well within the standard deviation parameter of the study.
	Mf ASSEP	• Underestimated pure tone at 0.5 kHz with 35 dB • Underestimated pure tone threshold at 1.0 with 25 dB • Underestimated pure tone threshold at 2.0 kHz with 5 dB • Underestimated pure tone threshold at 4.0 kHz with 10 dB	Significant. The threat of under-amplification in particularly the low, but also in the high frequency range would have been a very real possibility. Cochlear implant candidacy would have been overlooked as a management option. This is, however, mean data of a limited number of subjects and not indicative of the clinical utility of the MF ASSEP.

The use of Mf ASSEP was unable to provide clinically valid low frequency information in hearing losses that were predominantly low frequency or mid frequency (notch) orientated. The appropriate early management of these hearing losses would have been limited had the pure tone results not been available. Explanations for these discrepancies will be attempted within the remainder of the chapter by exploring the contributions of each components of the evoked potential procedure in more detail.

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6.3.1 The research question revisited: towards pure tone threshold prediction.

The research question posed in Chapter 1 read as follows: **Can thresholds obtained with dichotic Mf ASSEP translate into an accurate description of hearing when compared to pure tone thresholds and ABR threshold estimates in normal and impaired ears?**

With the presence of inferential measures such as evoked potentials and the introduction of complicating variables such as hearing loss on new technology such as Mf ASSEP, this question does not have a simple answer. For the purposes of this study and in an attempt to arrive at a logical conclusion, a schematic illustration of the contributing components was developed to allow for all the variables to be accommodated and to try reaching an answer. The schema is presented below.

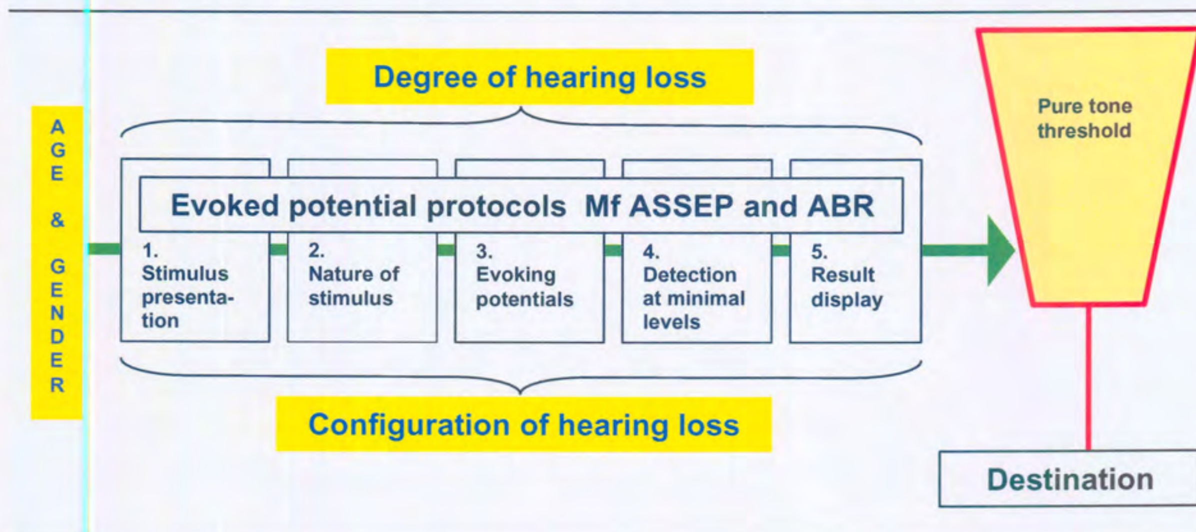

Figure 6.1 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

The pure tone threshold is visualized as a destination to which the evoked potential protocols should aim. En route to the pure tone threshold, four separate yet related

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variables can be identified, namely, age, gender, degree and configuration of hearing loss. In this study, the first two variables were controlled at the onset to ensure comparative value and to limit confounding effects. The latter variables require continuous accommodation and monitoring by the particular evoked potential technique. Tendencies that occurred at each of the various 'stations' along the evoked measure 'route' will be explored according to the various contributing factors and influences at each juncture to glean an answer to the research question of the study.

6.3.1.1 *Towards pure tone threshold prediction – Stimulus presentation*

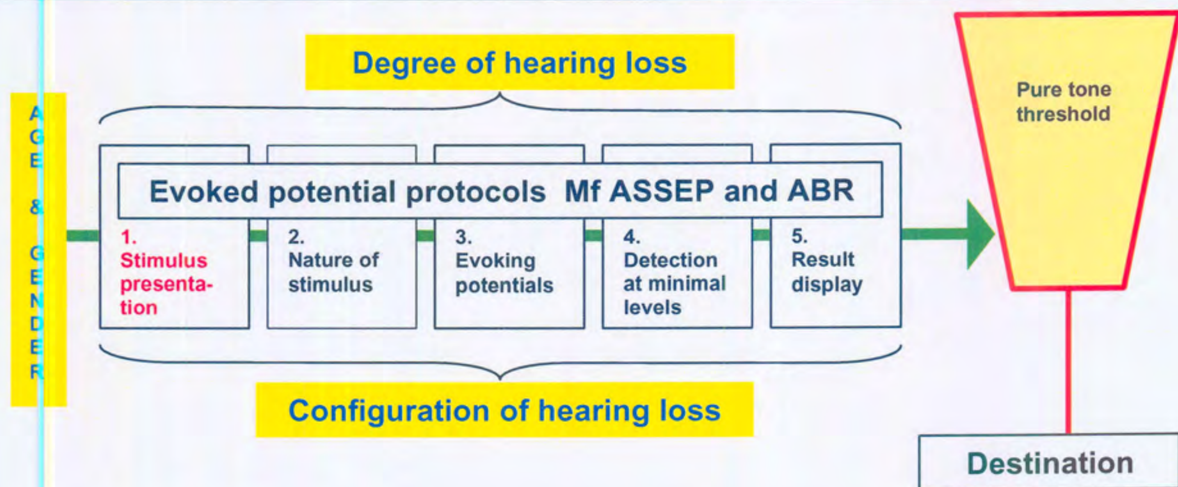

Figure 6.2 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

The first tendencies to be explored are related to the influences and contributions the **stimulus presentation** may have had on the results. Within this parameter three issues require highlighting namely

- The acoustic environment
- The transducer used

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- The use of monotic or dichotic stimulus presentation.

6.3.1.1.1 The acoustic environment

Most studies conducted on Mf ASSEP used pure tone as the gold standard. The pure tone test battery is usually conducted in soundproof conditions, while the Mf ASSEP protocol is conducted in a quiet or sound treated room with less than optimal noise levels. Comparative endeavors are thus often compromised by poor control of the test environment. Although noise levels usually degrade the electrophysiological response, hence the use of sedation to reduce artifact causing noise, manipulation of low filters and so forth, Picton et al. (1998) report the favorable recognition of Mf ASSEP in less than optimal conditions, contradicting the situation with ABR testing protocols. While this holds promise for implementing Mf ASSEP in clinical settings with different populations (for example nurseries and other hospitals wards), the validity of the technique should first be established with the test environment as a controlled test variable, not as a dependent test variable unless clearly specified as such. The current study used soundproofing throughout the study to ensure that the test environment did not influence the outcomes to a significant degree.

The control of acoustic ambient noise is critical in evoked potential procedures at threshold levels (Hall, 1992; Picton et al., 1998; Herdman & Stapells, 2001). In the field of audiology, the guidelines for, and the use of, standard uniform noise control measures have been strangely elusive. The use of double or single proofing in acoustic booths meets ANSI standards for hearing assessment. The effect of double versus single walling in the acoustic environment does, however, show difference in threshold. There is agreement that the careful management and set up of the testing environment is essential in conducting standardized, valid and reliable testing (Hall, 1992; Hood, 1998).

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As the effect of age, gender, degree of hearing loss and configuration of hearing loss are systematically manipulated to determine the effectiveness of the procedure, ambient acoustic noise levels should be reduced and eliminated to the extent that they do not confound the obtained results.

In evoked potential techniques, noise reduction is an ongoing clinical concern. Many techniques have been developed to ensure reduced noise levels, ranging from sound proofing, to filtering, patient instruction and even patient sedation to list a few. The primary and most obvious of these techniques entails the use of a controlled acoustic environment.

Possibly due to the novelty of the dichotic Mf ASSEP technique, only two studies were conducted that employed the dichotic technique across the degree spectrum of hearing loss, namely Herdman & Stapells (2001) and Perez –Abalo et al. (2001). Their acoustic environments differed considerably. Herdman & Stapells (2001) employed a double-walled sound attenuated booth, which recorded low noise levels of 10-12 SPL across 0.5-4.0 kHz octave band. In their conclusion as to why their study indicated relatively small differences between Mf ASSEP and behavioral thresholds, they specifically cited the low noise levels of their acoustic environment. The study conducted by Perez-Abalo and colleagues (2001) was conducted on a large scale with a large number of subjects across the severity of hearing loss range, yet surprisingly their threshold procedures were obtained in a sound treated room without sound attenuation. In their report they acknowledge high ambient noise levels of 65 and 71 dB SPL but they nevertheless continue their discussion of the correlation indicating the clinical utility of the Mf ASSEP technique. This is disappointing because it would have been worthwhile to examine the

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results of 43 hearing impaired children between 6 and 15 years of age without a nagging suspicion of the confounding influence of the acoustic environment.

One explanation as to why the influence of the noise environment was disregarded in the Perez-Abalo et al. study (2001) may be related to the orientation of the researchers. In Cuba where their study was conducted, the profession of audiology does not exist and the testing of hearing falls in the domain of the ENT medical doctors or the neuro-physiologists (Perez-Abalo, 2001, personal communication). Both these professions cover a broad range of testing protocols where the use of carefully controlled acoustics environments may or may not be stressed to the same extent as in the field of diagnostic audiology. The students of audiology are exposed during both their under- and post-graduate training to the standards and specification for conducting hearing assessment procedures required for board certification. Unfortunately, the emphasis is all too often placed on establishing low impedance levels between electrode and scalp, while the obvious requirement for quiet in the testing environment is acknowledged and then dismissed.

Another explanation for the poor control of the acoustic environment is related to the workplace. In most clinical studies, researchers are forced to make use of an existing acoustic environment, which is often not ideal. Neglecting to incorporate the effect of the testing environment on results remains controversial and it may provide a challenge to ensure compatible results with existing literature. The introduction of weighting factors and continual measurements of ambient noise that may be statistically manipulated to ensure validity need to be considered for clinical studies in particular (John & Picton, 2000).

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The current study employed a single walled sound attenuated booth for the determination of pure tone thresholds and to ensure reliability. The results were compared to the audiogram obtained in the subject's educational environment in a double walled sound attenuated booth. No discrepancies were evident. The evoked potential procedures with its higher susceptibility to noise because of their onset response and far field nature (Hall, 1992) were conducted in a double walled sound attenuated booth within a sound treated room. Low ambient noise levels were, therefore, evident. According to Frank (2000) a reduction of 20-30 dB in external ambient noise is evident with double walling but he did not discuss the use of sound treatment additional to sound proofing. Picton et al. (1998) acknowledge the inadequate reduction of noise with the recording techniques employed by them and other researchers. They propagate reconsideration of recording techniques – still without the primary consideration of an optimal testing environment prior to the adjustment of stimulus and recording parameters.

A further noteworthy comment by the same author also relates to the pervasive noise problem during Mf ASSEP and other evoked potential measurements. They postulate that the noise should be studied first as a source of additional information instead of being eliminated without the slightest consideration of its content (Picton, 2001). These suggestions are seductive as, despite tremendous gains in the sophistication of recording procedures and requirements for optimal recordings, ambient noise remains a factor. The presence of 3 Hz beats and brain noise need to be examined at threshold level as this may lead to clearer speculations and understanding of the neurophysiology of hearing in normally hearing and impaired ears.

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6.3.2.1.2 Transducer

Frequency shaping by the transducer can shape the response spectrum for evoked potentials (Gorga et al., 1985). Air conducted amplitude modulated tones can be presented through supra-aural headphones (as in the current study), insert earphones (Herdman & Stapells, 2001), or the free field (Picton et al., 1998) in threshold seeking procedures. Frequency shaping by the transducer is evident in ABR procedures using broadband stimuli like a click indicating a high frequency emphasis around 3 kHz (Hall, 1992; Oates & Stapells, 1998; Gorga, 1999). In the current study the ABR click showed highest correlation with the pure tone thresholds between 2 and 4 kHz, yet had above average correlation at 0.5 kHz and 1.0 kHz as well. This may indicate the click stimuli seeking our 'best hearing' frequencies in the presence of impairment.

The use of insert earphones are recommended over supra –aural headphones (Hall & Mueller, 1997; Hall, 1992) yet many studies (Lins & Picton, 1995; Lins et al. 1996; Rance et al., 1998; Perez- Abalo et al., 2001) employed supra-aural headphones on normally hearing adults, hearing impaired subjects and even infants. The current study made use of supra-aural headphones because of manufacturer specification. The version of the equipment utilized did not allow for any stimulus presentation mode other than supra-aural headphones. Finally it should be noted that Herdman & Stapells (2001) used insert earphones, which, despite the increased patient comfort during testing, seemed to have little effect on the accuracy of the results.

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6.3.1.1.3 Monotic versus dichotic stimulus presentation.

The current study used the dichotic testing condition for Mf ASSEP and monotic testing for the ABR. The use of dichotic stimulation did not seem to have an effect on the accuracy of the results in either the degree or configuration categories used in the study (Tables 5.11 and 5.14). Previous findings have indicated that no difference in amplitude occurs in the Mf ASSEP during multiple and single testing conditions (Lins & Picton, 1995), provided that the intensity is maintained at low to moderate levels (John et al., 1998) and that interaction at threshold levels is not disregarded completely. Although John & Picton (2000) caution against the unknown effect of high intensity levels on multiple stimulation, they do not, in fact, assess differences at high intensities, as their subjects were not hearing impaired. During their study they did not exceed comfort levels for their subjects, hence disallowing hearing impairment's confounding effects on sensation levels, dynamic range or intensity.

Perez-Abalo et al. (2001) and Herdman & Stapells (2001) used the dichotic presentation technique in normal and impaired ears. No significant differences in response amplitude between monotic and dichotic testing conditions were identified. This indicates agreement with Lins & Picton's statement (1995) that "*stimuli differing in ear of presentation or carrier frequency may be presented simultaneously without significant loss in amplitude....in stimuli that were as little as an octave apart*" (p429.) Corroboration could not be found in research conducted by Lins et al. (1996). While these researchers had the dichotic stimulation option available in their clinical study, their hearing impaired subjects and simulated hearing loss subjects were tested in the monotic condition.

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The advantage provided by the dichotic stimulation is the significant reduction in testing time. It would imply the testing of four frequencies in each ear simultaneously while the number of presentations would be dependent on the degree and configuration of hearing loss. Irrespective of the degree or configuration, the testing time would be reduced when compared to ABR.

Even though the reduction of testing time through dichotic stimulation holds exciting possibilities, three concerns need to be highlighted at this juncture. Firstly, the effect of exposure to a multiple dichotic stimulus at high intensities has not been explored in terms of the well documented negative effect of sustained exposure to noise. Secondly, the carriers are presented at the same intensity, which could be a problem when the full range of configuration of hearing loss is examined. For example, a steeply sloping high frequency hearing loss may require high intensity levels to record responses at the 2 and 4 kHz points, while the 0.5 and 1 kHz levels may not be as significantly affected. Patient discomfort is, therefore, a concern. Picton et al. (1998) postulate that the multiple stimulus technique encounters difficulty when presented with a steeply sloping loss with same intensity presentation. In order to accommodate this phenomenon, they propose introducing an algorithm that would adjust intensity of the particular carrier frequency once a response is recognized as present until the audiogram is approximated. This calculation holds promise, but still does not indicate the specific starting intensity of the Mf ASSEP test procedure when considering a sloping or notch shaped loss.

The use of dichotic stimulation implies the adjustment of electrodes on the scalp. While John et al. (1998) made use of the nape of the neck for reference, Peres-Abalo et al. (2001) and the current study used the Oz position at the back of the head for reference. In retrospect, the use of the nape of the neck in the current study's adult population may

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have been the better option, as it increases patient comfort during testing and also limits excessive exfoliation. The study was conducted according to manufacturer specification, but low ambient and muscle noise were present in the current study, even though the nape of the neck provides less interference with recording techniques (Hall, 2001, personal communication).

The third concern relates to the complete lack of diagnostic data of the dichotic effect on developing neural pathways. The use of multiple stimulation is contra-indicated in infants as the effect of the immaturity of the neural pathways on dichotic stimuli has not been conceptualized at present. The use of monotic stimulation is, therefore recommended in newborn screening and infant testing (Rance et al, 1995; Perez-Abalo, et al. 2001, personal communication).

6.3.2.2. Towards pure tone threshold prediction - nature of the stimulus

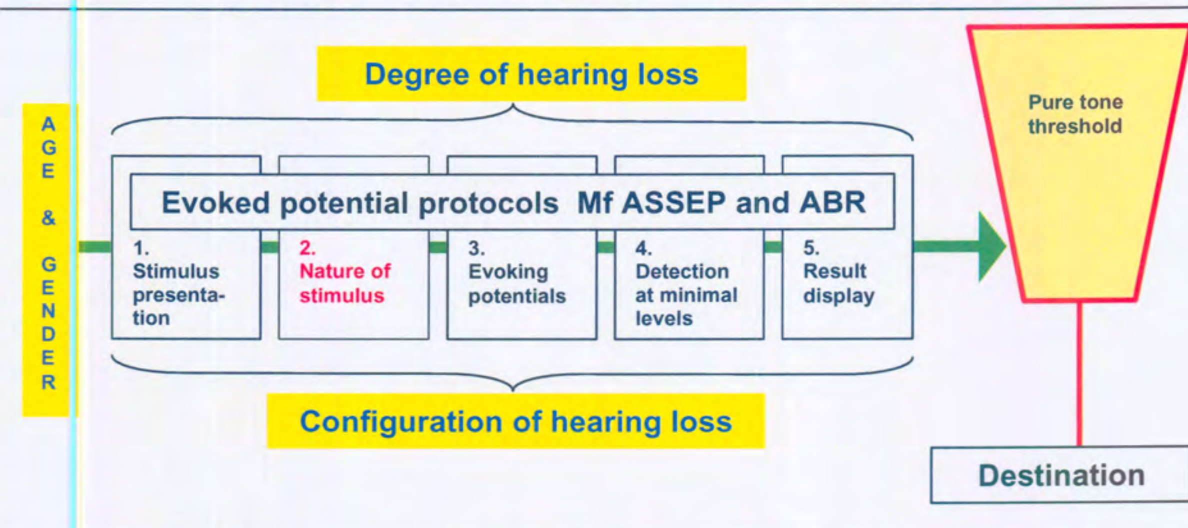

Figure 6.3 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

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The influences that will be highlighted in the following discussion are:

- Stimulus duration
- Stimulus complexity
- Stimulus frequency
- Stimulus intensity
- Stimulus modulation.

6.3.1.2.1 Stimulus duration

In each testing condition in the current study, the stimulus duration was varied in semi-random fashion. The click ABR used a stimulus of less than 1 msec (see Table 4.7 of Research Method), the tone burst at 0.5 kHz was 2 ms (see Table 4.10 of Research Method). The Mf ASSEP used a continuous tone modulated at 70-90 Hz (see paragraph 4.6.3.1.1 of Chapter 4), while the pure tone stimuli exceeded 200 msec, even though the exact duration of the pure tone was never measured.

Caution is necessary when comparing different test protocols, as the effects of stimulus duration are often dismissed in the target of predicting the pure tone threshold in difficult-to-test populations. ABR procedures enlist the earliest portion of the stimulus to obtain minimum responses (Gorga et al., 1984). Brief broadband stimuli are suitable for assessing neural synchrony or the simultaneous firing of neurons up to brainstem level, with the inferential secondary purpose of estimating hearing sensitivity. The brief tone burst attempts a compromise between neural synchrony with some frequency specificity. The use of these short latency responses (between 1 and 15 ms after stimulus onset) show no susceptibility to state of arousal or maturational status (Hall, 1992; Hood, 1998), hence its high suitability for use with young infants and other difficult-to-test patients.

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The nature of the continuous amplitude modulated tone of the Mf ASSEP eliminates the abrupt stimuli changes over time of ABR stimuli, which cause signal distortion through the amplifiers. This may facilitate the processing of stimuli which, in turn, holds possibilities for the clinical implementation of Mf ASSEP in the free field condition to obtain aided audiograms through hearing aids as well as cochlear implants (Rance et al., 1995; Picton et al., 1998). The effects of arousal and maturity, however also affect the Mf ASSEP, but these effects can be overridden by manipulation of the modulation rate. At slower modulation rates, the 40 Hz response, maturational and state of wakefulness effects occur, but when the modulation exceeds 70 Hz, no effects are evident (Rance et al., 1995; John & Picton, 1998).

Pure tones have a duration in excess of 200 mecs, and, according to Viemeister & Wakefield (1991), the decrease in pure tone threshold will increase stimulus duration. They ascribe this finding to the integration capability of the ear that, with longer duration, are afforded multiple 'examinations' of the stimulus.

Against this background, it can be argued that theoretically the pure tone thresholds would be the most accurate reflection of frequency specific hearing based on the influence of stimulus duration, hence its designation as the gold standard. The continuous tone of the Mf ASSEP would be a close second to the pure tone data, as well as with the tone burst at 0.5 as approximations of frequency specific hearing. The click would possibly be the closest to the pure tone 'data points' especially in the high frequencies, without indicating any frequency specific information.

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These findings were evident in the degree categories of the current study. In some of the configuration categories, however, the pure tone thresholds were underestimated, particularly in the low frequencies.

6.3.1.2.2 Stimulus complexity

The complexity of the stimulus did not have an effect on the degree (Table 5.11) or configuration (Table 5.14) of hearing loss categories of the current study. This finding may have everything to do with the domain in which the potentials were recorded.

In the time domain, such as used in ABR, the complexity of scalp recordings of different stimuli superimposed on one another will be difficult to separate. The use of Fast Fourier Transform in the frequency domain, however, enables response separation, as each response would occur at each designated modulation frequency. The amplitude and phase of the response is then automatically measured, using for example the F-test, in its signal to noise context at a particular modulation frequency in the frequency domain (Lins & Picton, 1995).

Picton et al. (1998), John & Picton (2000), Lins et al. (1996) and Herdman & Stapells (2001) established that the multiple stimulus condition exhibits little effect on amplitude of responses, provided that the frequency differences exceed an octave and the intensity level is monitored have established. In such a scenario, four stimuli can be presented to each ear simultaneously without significant loss in amplitude. Lins and Picton (1995) acknowledge the occurrence of interaction between different stimuli in different ears, but these dichotic effects were small and could not be replicated in their study. The use of high intensities may have exacerbated the interaction effect between stimuli. Yet the ABR thresholds levels were also the least reliable representations when levels exceeded

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90 dB, even though the stimulus was simple. Inaccuracies in these cases could possibly be attributed to high intensity levels and not to complexity of the stimulus *per se*.

6.3.1.2.3 *Stimulus frequency*

Particular attention was given to any studies shedding light on the effect of stimulus frequency, as the current study found some discrepancies in prediction of thresholds in certain configurations – notch and low frequency (paragraphs 5.7.1 and 5.7.2 of Chapter 5 respectively). Contradictory findings are, however, evident in the literature regarding the effect of stimulus frequency on Mf ASSEP.

There are reports of larger amplitudes of responses for high frequency information (Rance et al. 1993; Rance et al., 1995) in the single stimulation condition, lower amplitudes in low frequency information in the multiple stimulation condition (John & Picton, 2000), variability in high frequencies in the multiple condition (Picton et al. 1998), and even abnormal elevation of high frequency thresholds in the multiple condition (Picton et al., 1998) and abnormal elevation of low frequency thresholds in the single condition (Rance et al. 1993). Scant explanations are provided by Rance et al. (1993) as to why they experience underestimation of pure tone threshold in the low frequencies, while Picton et al. (1998) and John & Picton (2000) also attempt explanations.

There are two important considerations in this regard namely: a) the activation of the basilar membrane and b) the mediation of responses on the basilar membrane. In the current study, the Mf ASSEP tended to underestimate threshold in certain frequency regions in two categories. Stated differently, the predicted response is 'better' and 'bigger' than the actual pure tone threshold. Similar findings were reported by Rance et al. (1993; Rance et al.,1995), even though they used the single stimulus condition. In

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contrast to the current study and to the work conducted by Rance et al. (1993), John & Picton (2000) found that responses to lower carrier frequencies of 500 and 750 Hz were lower in amplitude than others, and that these carrier frequencies have lower effective intensity levels. They argue that the lower carrier frequencies evoke an activation pattern on the basilar membrane, which includes a larger spatial extent than higher carrier frequencies. Because neurons along a broad area of the basilar membrane will individually respond to the same particular carrier frequency, some of the neurons may be activated significantly earlier than others (John & Picton, 2000). The subsequent latency jitter of the response might then attenuate the amplitude of the compound response. These processes seem not to be affected by multiple or single stimulus conditions, provided that an octave separation between carrier frequencies is maintained (Lins & Picton, 1995). The effect of intensity was not considered as their research focused on moderate intensity levels to avoid interaction. The published results of the Rance group, are, therefore, more significant, as their subjects were all cochlear candidates with little or no residual hearing using ABR techniques. It seems that intensity may influence the lower frequencies to some extent. As evident on the severe and profound categories of this study, it would be prudent to perform the Mf ASSEP procedure on these categories by comparing single versus dichotic multiple stimulation.

The foregoing argument is plausible, although it does not explain the overestimation of threshold in the low frequency categories (see Sections 5.6.5 and 5.6.6) but rather contradicts it. A possible explanation that may provide some insight into this issue is also provided by Picton et al. but in a previous article published in 1998. He extrapolated some findings of previous work in neurophysiology conducted by Kiang and Dallos and Harris in the late 1970s.

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The argument presented pertains to the presence of abnormal tuning curves in the cochlea. This allows for high frequency areas to maintain their cut-off slopes, while the low frequency areas lose their high sensitivity tip at the carrier frequency, allowing for responses to low frequency stimuli to be mediated through places on the basilar membrane that are place specific for high frequency information. While this phenomenon is evident in normal cochleas at high intensities, it may be present in damaged cochleas at minimum response levels. This may cause responses to be abnormally elevated in the high frequencies. Findings of the current study did experience abnormal elevation of high frequency threshold data in one category. The presence of unstable abnormal tuning curves and the subsequent abnormal mediation patterns on the basilar membrane could, therefore, account for the discrepancies evident in some of the pure tone and Mf ASSEP data, particularly at high intensity levels in the multiple condition. The phenomenon will be discussed in more detail in Detection at minimal response levels and the effects of recruitment.

Another possible explanation is presented by Rance et al. (1993). They also experienced some underestimation of low frequency responses using monotic stimulation and they concluded that responses to these frequency specific stimuli are likely to be originating from the appropriate places in the cochlea. It is interesting that they did not have the confounding effect of multiple stimulation presented dichotically and still experienced difficulty in the accurate prediction of low frequency threshold levels. More research in this regard is clearly indicated.

In terms of high frequencies, Rance et al. (1995) found better correlation coefficients, and more reliability in responses in the high frequencies with more accurate predictions, using monotic stimulation compared to the current study. Picton et al. (1998), however,

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experienced variability in 4000 Hz responses in the multiple condition with no response recognition even above threshold. They subsequently adjusted their stimulus form dichotic to monotic and managed to record 4000 Hz. It seems that the high frequencies have less variability in the monotic condition, when recorded singly. The current study had no variability or incongruencies in the multiple condition in the high frequencies, even at high intensity levels, with the exception of one category.

The stimulus frequency effect in the ABR protocol was less profound. As expected, click stimuli showed little frequency specificity. Despite its much published advantages and disadvantages, its inclusion in an evoked potential test battery is recommended, often as the logical starting point to conduct further testing in the absence of reliable, inconclusive pure tone results (Hall, 1992; Gorga et al., 1993; Hall & Mueller, 1997; Hood, 1998; Gorga, 1999). The use of a click-evoked ABR as primary diagnostic tool in amplification determination is, however, clearly not indicated (Gorga et al., 1993).

6.3.1.2.4 Stimulus intensity

The intensity of the stimulus did not affect the accuracy of the results in either the degree or configuration categories of the study as evident through the statistical procedures employed in the study (see Tables 5.11 and 5.14). This is a particularly interesting finding especially in the Mf ASSEP condition, as most of the existing clinical research employed moderate to low intensity sounds (Picton et al., 1998) or a limited representation of various degrees of hearing loss (Perez-Abalo et al., 2001). The ability to use high level stimulus intensity was one of the key advantages over ABR testing when used monotically, as evident in work conducted by Rance et al. (1998) on cochlear implant candidates. The fact that those responses could be found at high intensities in the absence of ABR thresholds was indicative of some residual hearing and an

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indication of a better ear or, in fact, a total hearing loss. These findings have not been sufficiently replicated in the dichotic stimulus condition until this study. As reported in the aforementioned studies, limited output of the ABR test protocol often showed no response at high intensities or could not be determined because of the presence of excessive stimulus artifact. No responses were recorded using Mf ASSEP, but to a lesser extent in some of the frequencies. No single case showed no responses across the frequency spectrum using Mf ASSEP while the tone burst and click ABR results were unobtainable. In the Mf ASSEP test condition, the no responses were documented within the severe to profound hearing loss categories, and on close examination of a particular threshold, rather than the pure tone average, the threshold fall within the profound hearing loss category.

The careful control of stimulus intensity in the multiple condition in previous studies (Lins et al., 1996; John & Picton, 2000) relates to limitations on the occurrence of interaction of sounds in the basilar membrane. Research conducted by Lins & Picton (1995) reports some interaction in ears in different frequency regions when the stimuli are presented dichotically. These interactions were, however, not replicable and seemed to affect high frequencies more than low frequencies – a tendency perhaps evident in the minimum response levels of the low frequency and notch categories.

Moore (1993) supports the notion of interaction on the basilar membrane, but states that interaction is a consideration in high intensity stimuli - loud sounds should interact, and that increase in intensity should increase the interaction, despite every effort to control the separation of the carrier frequencies, hence the continuous use of moderate stimulus intensities. The cause of the interaction resides in simple physiology, namely, that the cochlear filter widens at higher intensities. Furthermore louder sounds allow a more

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rapid rise in synaptic potentials because of the release of more transmitters or an increase in stimulus activation patterns (John & Picton, 2000).

The close proximity of all the structures of hearing within the inner ear logically supports the presence of interaction. It is obvious that multiple, simultaneous high intensity sound may cause secondary movement within the structure of the inner ear, particularly on the basilar membrane. This phenomenon has recently been hypothesized in a study when the exposure to loud sounds has resulted in vestibular symptoms in noise induced hearing loss due to the proximity of the inner ear structures (Strachan, 2001). The question has remained unanswered up to now: whether this interaction significantly influences the results when high intensity procedures are undertaken using Mf ASSEP. The current study found no evidence of significant interaction.

One suggestion to eliminate the occurrence of spurious (present by chance due to interaction) responses would be to increase the averaging of the signals to eliminate interference of artifact and related EEG activity (John & Picton, 2000). At these intensities, however, the concern should be for noise exposure with an increase in averaging and consequently in testing time; especially when using multiple dichotic stimuli presented at high intensity levels (Picton, 2001).

Deliberate caution should be applied when testing at high intensities to ensure accommodation of the configuration of the hearing loss. A steep sloping hearing loss may cause patient discomfort when stimuli are presented at equal intensities across the frequency spectrum. In such cases, the pure tone average should serve as a clinical indicator, and the need for some corroboration of behavior to sound in low and high frequency ranges should be considered.

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6.3.1.2.5 *Stimulus modulation*

Three related aspects of stimulus modulation demand to be reviewed within in a clinical context in this section namely that *modulation is compulsory, requires audition* and *reduces sound intensity*. Each of these will be addressed briefly in the context of the current study.

Steady state recordings are dependent on stimulus modulation as the steady state potential is evoked by modulation of the carrier rather than the occurrence of the carrier (Picton et al., 1998). Furthermore, the modulation needs to be audible before the steady potential is evoked. The frequency spectrum of the amplitude-modulated tone consists of the carrier frequency and two side bands (half the amplitude of a 100% AM tone) that are below the intensity of the carrier frequency. If the side bands are not audible, no response detection is possible. As modulation may not become audible well above threshold level, it is logical to expect the steady state potential to be elevated above the expected threshold level of an individual. It is also expected to be at higher intensity levels, as the use of amplitude modulation reduces actual intensity. The expected conclusion is therefore that steady state would also be elevated above threshold levels because of the requirements of amplitude modulations audition and the fact that is intensity increase is necessary to provide the same audibility (Picton et al., 1998).

While the use of stimulus modulation (amplitude and in some cases frequency modulation) is a well-described phenomenon in monotic and dichotic Steady State procedures, its use is rarely extended to other measurements in clinical studies. In most studies, the Mf ASSEP results are elevated above the pure tone results, with better correlation in pathological ears due to abnormal loudness growth. This elevation-correlation relationship was evident in the current study, as 100% amplitude modulated

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tones in the recording of Mf ASSEP were used, similar to the recording procedures of Lins et al. (1996) and Perez-Abalo et al. (2001). While the additional use of averaging and maximum length sweeps (Picton et al., 1998; Herdman & Stapells, 2001) additional to optimal reduction of noise could increase correlation between pure tones and Mf ASSEP, an inherent discrepancy between the two would persist due to modulation. Picton et al. (1998) postulate that no recognizable responses would be present within 10 dB HL, irrespective of the number of averages, as there may be too much latency jitter in the modulation of the response to allow averaging procedures to facilitate response detection. Although this provides a logical dead end to correlation, Herdman & Stapells (2001) achieved better correlation between pure tones and Mf ASSEP. In addition to introducing most recommendations in the literature, namely, longer averaging, low background noise and maximum sweep protocol, they also employed *amplitude modulated* pure tones to obtain their pure tone results.

AM pure tones contributed significantly to the correlation between the Mf ASSEP and pure tone results in the Herdman & Stapells report (2001). According to Lins et al. (1995), AM pure tones show an elevation of 5 dB compared to pure tones obtained by traditional audiometric techniques in for instance Perez-Abalo et al. (2001) and the current study. While the use of AM tones was a creative means of exploring minimum response level correlation, it does not render a clear clinical protocol for use in difficult-to-test populations, as the use of a method with documented elevation of at least 5 dB would cause confusion and the introduction of arbitrary correction procedures not viable for the clinical setting, The use of AM tones by Herdman & Stapells, (2001) reduces the clinical application of their results. It would have been more prudent to use AM as well as standard pure tones in their test protocol. While they only used ten adult subjects this could have been feasible without adding unnecessary testing time.

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6.3.1.3 Towards pure tone threshold prediction - evoking potentials

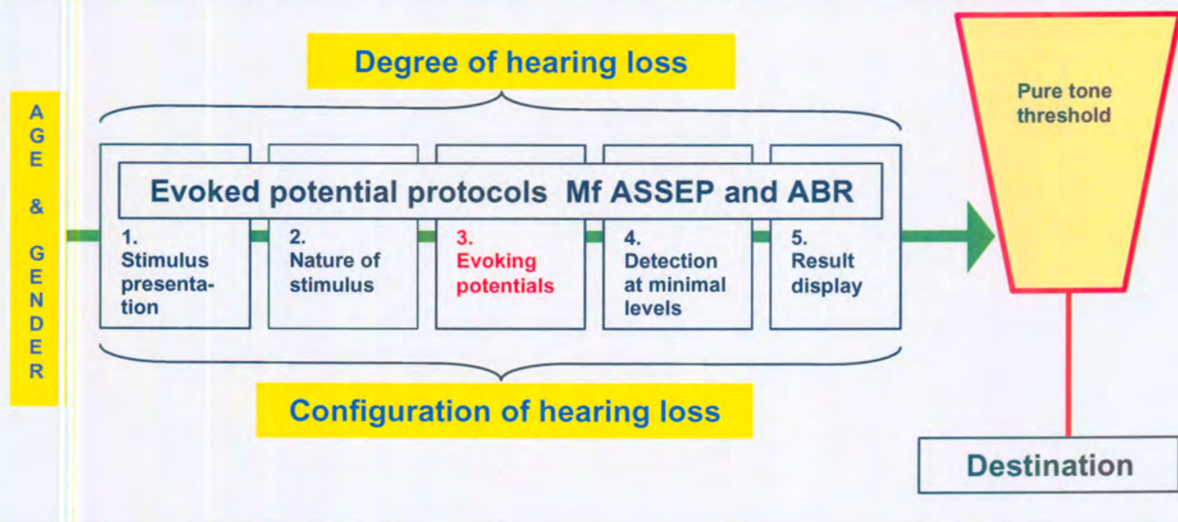

Figure 6.4 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

After the stimulus presentation and the stimulus itself have been addressed in the testing situation, two essential ingredients need to be added to ensure optimal recording of evoked potentials:

- Sufficient quietude
- Adequate averaging.

Muhler, Pethe & von Specht (2001) report great variability of input background noise in inter- as well as intra-subject measurements. They suggest the use of predefined levels of residual noise and the inclusion in all published data of residual noise estimates. With the wisdom of hindsight, the results of the current study underline this statement. Soundproofing was applied in all testing conditions, and the noise levels were kept at a minimum, although no formal measure of noise was performed, which would be a consideration for further studies.

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The following fundamental questions need to be addressed, namely:

- What is deemed sufficiently quiet for recording an evoked potential using dBA?
- How many averages are required at the very least to ensure adequate averaging?

Both noise and consequent averaging are poorly defined in the clinical setting. No quantitative measures or standards exist in the use of evoked potential measurements to control these variables, hampering optimal comparisons across studies.

Previously in this chapter, the differences between using of single and double proof testing booths were addressed (Section 6.3.1.1.1.). Though double proofing should theoretically increase the accuracy of results, the difference is marginal in the current study in both the ABR and Mf ASSEP protocol (single proof) and the pure tone results (double proofing). Had the ABR or the Mf ASSEP been conducted in a double proofing environment, comparison would have been hampered in a much more significant manner.

A limitation identified in this study and also evident in the literature, relates to quantification. The following noise requirements could be quantified in the current study – electrical noise should be kept below 0.010 micro Volt, and above this level no responses could be deemed reliable. With regard to the noise levels within the booth when the stimulus is introduced, no formal measures were undertaken. With poor noise control, the confusion spills over into the number of averages required to ensure optimal testing conditions. The more noise present, the more averaging is required. Yet it remains important to determine how much noise and how much averaging is needed.

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Murky noise specifications in clinical studies can lead to extremely arbitrary judgments regarding averaging. Combined with the ever present consideration of testing time in especially difficult-to-test populations, the averaging procedures are more related to 'gut feel' than standard. It is thus not surprising that the use of increased averaging arises as a possible solution to inferentially improve poor correlation between pure tone and evoked potential results by increasing the accuracy of the evoked potential results. The introduction of increased averages primarily reduces background EEG noise, as well as existing extraneous noise levels that could not be limited by other techniques such as electrode placement filter settings and testing environment modification.

The current study used standard averaging in both the ABR and the Mf ASSEP protocols to ensure comparison with literature findings and also to remain within the clinical paradigm that necessitates continued consideration of testing time (see paragraphs 4.6.2, 4.6.3.and 4.6.4. of Chapter 4). Mf ASSEP and pure tone correlation were within the significant range using statistical measurements across the frequency and degree spectrums. Poorer but still statistically significant findings were evident in the ABR tone burst and ABR click correlation to pure tone results. From the foregoing, it can be concluded that sufficient quietude and adequate averaging were employed. The obtained results were therefore primarily indicative of the specific degree and particular configuration combinations and not due to excessive noise levels or limited averaging.

At this juncture, the difference in averaging procedure evident in some of the key articles using Mf ASSEP compared to pure tones need to be considered. An EEG sweep for the current study is similar to that employed by Perez-Abalo et al. (2001), and this may be ascribed to the identical equipment set-ups that were used, namely, 11.4 seconds. Herdman & Stapells (2001) performed longer averaging at 16.38 seconds per single

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sweep. Response identification ranges between minimum and maximum sweeps and higher numbers of sweeps are usually required for stimuli near suspected threshold levels. Conversely significant responses were only confirmed after the minimum sweeps were averaged and no response status is only confirmed once the maximum number of sweeps had been averaged. Herdman & Stapells (2001) used maximum sweeps and the longest duration possible per sweep. Combined with the amplitude modulation in the pure tone protocol, the close correlation between their the AM pure tones and the Mf ASSEP may be explained. According to Picton et al. (1998), increased averaging in Mf ASSEP would not reduce correlation to within 10 dB of the pure tones, as is the case with ABR (Elberling & Don, 1987), due to excessive latency jitter in Mf ASSEP at minimum response levels.

Herdman & Stapells (2001) did, however, prove Picton et al. (1998) wrong when they recorded Mf ASSEP within 10 dB of the pure tones. The specific contribution of the use of AM pure tones, the use of longer sweeps or the use of maximum averages cannot be separated and ordered. The improved results reported a significant increase in testing time. Testing time of almost three times the duration of the Perez-Abalo et al. (2001) and the current study was reported, hampering the clinical introduction of this specific sweep and averaging protocol in difficult-to-test populations such as pediatric clients where time is of the essence. The words of Hall & Mueller (1998:327) summarize the sentiment: Whatever works, do it, and *(when considering pediatric assessment*) whatever works, do it quickly (parentheses mine).

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6.3.1.4 Towards pure tone threshold prediction - detection at MRLs

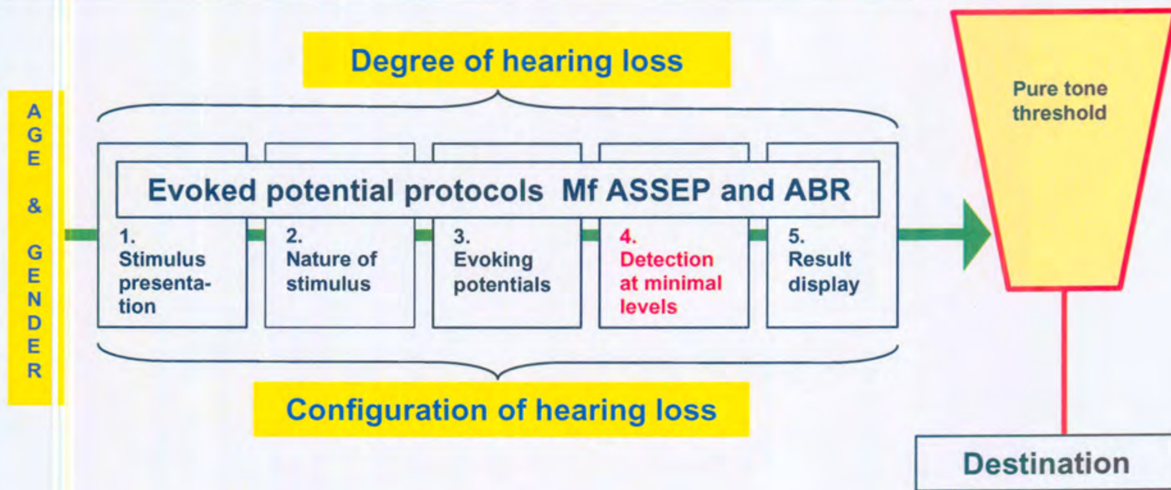

Figure 6.5 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

Three issues will be highlighted in this section:

- The detection method
- Why pathology in the cochlea facilitates response detection
- The occasional presence of spurious responses.

6.3.1.4.1 The detection method: subjective wave analysis versus automatic response detection

The elimination of the human factor in the detection of responses is an obvious advantage that is documented in most of the clinical studies using steady state techniques. Conversely, the problems associated with the subjective waveform analysis required from ABR procedures are juxtaposed within this context. The information obtained is frequency specific, but the detection of minimum responses at threshold level necessitates expertise and the implementation of strategies to ensure reliability and

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validity (Wilson, 2000). Achieving these in the clinical setting is difficult because of time constraints and the apparent insensitivity to the benefits of these strategies.

The tone burst ABR can be introduced at as many frequencies as required although low frequency information such as 250 Hz is not recommended (Hall, 2001, personal communication; Hood, 1998). However, the time requirement for firstly performing a threshold seeking procedure at various frequencies, and secondly obtaining norms for the particular clinical setting and thirdly in accurately detecting minimal responses in normal and pathological ears are hampering the regular introduction of tone burst ABR into the clinical test battery.

While the current study clearly indicates that the automatic response detection of the Mf ASSEP presented with accurate findings when compared to pure tones, waveform analysis of the ABR did not produce poorer reflection of pure tones when response detection was the consideration. However, the current status of the world we live in is also reflected in the field of diagnostic audiology, this being the continued pressure to test, average, detect and rehabilitate faster. Steady state testing in the frequency domain rises to this challenge quite successfully with the use of automated detection techniques in addition to multiple stimuli and dichotic testing possibilities. Automated detection certainly reduces testing time, the need for repeatable waveforms and *post hoc* analysis of results. On-line audiogram approximations are possible and it is conceivable that once the patient enters the booth and the testing begins with adequate noise levels and averaging procedures in place, s/he will leave with results across frequency spectrum in hand. Testing time, therefore, represents response detection time.

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The same cannot be reported for an ABR protocol. The introduction of wave rating scales, between rater judgments and the consultation of the ever-handy normative data file increases the time between testing commencement and final diagnosis. While this is definitely the case with click stimuli, the waveforms morphology is significantly reduced in attempts to obtain frequency specific threshold estimates using, for instance, tone bursts. The influence of frequency testing within the tone burst context further hampers waveform analyses, with low frequency waveforms being of poorer quality than high frequency waveforms (Hall, 2001).

Automated response detection does not require expertise and experience in the visual inspection of threshold level waveforms, as is the case with ABR. While the use of diagnostic ABR should be limited to experienced audiologists, a wider range of professionals with various degrees of experience may use Mf ASSEP.

In the current study, both techniques were employed and it was evident that the Mf ASSEP technique produced significantly larger quantities of diagnostic information in 20 minutes than the ABR protocol. The actual testing using the ABR protocol did not take long because of the limited stimuli used in the study. However, the waveform analysis, consisting of initial identification of wave V at all intensities, followed by a three rater blind study to ensure accurate threshold prediction for all ears (50 normally hearing and 50 pathological) at two testing points (click and tone burst), at all intensity levels (approximately 6 for the normal ears and three to six for pathological ears) needed considerable lengths of time to complete.

The availability of automatic response detection is not without problems, and the presence of detected 'responses' when there is no response present is described by

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Picton et al. (1998). The occurrence of spurious responses (Picton et al., 1998) will be discussed as the logical final component of this section (see 6.3.1.4.3).

6.3.1.4.2 Pathology in the cochlea facilitates MF ASSEP

ABR measurements obtain the clearest waveforms in normal ears, and significant compromise of morphology occurs in the presence of pathology in the middle ear (poor morphology, later occurring waves), inner ear or nerve of the ear (abnormal waveforms, compromised inter peak latencies or absent waveforms) (Hood, 1998). Mf ASSEP does not exhibit a similar pattern in the presence of inner ear damage.

Better correlation is evident in the mild to profound hearing loss categories and pure tones compared to the same correlation in normally hearing ears. It appears from the data from this study, as well as findings by John & Picton (2000), that the Mf ASSEP technique 'favors' pathology in the prediction of accurate hearing, certainly in mild and moderate hearing loss. Picton et al. (1998) offer some explanation for this phenomenon, which is also evident in their clinical studies using Mf ASSEP.

They considered three possible reasons for this occurrence, the first being unfavorable signal-to-noise ratios as a possible explanation, yet dismissed on the basis of their use of soundproofing in all testing conditions. The signal-to-noise dilemma is more evident in data of normally hearing subjects recorded when the pure tones are collected in quiet rooms (rather than soundproof rooms) favoring the Mf ASSEP, masking as a mild hearing loss with recruitment (Picton et al., 1998).

As a secondary consideration, age was examined. Hood (1998) reported relatively consistent evoked potential recordings in the age range of 10-60, but the onset of

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presbycusis in the fourth decade of life may have some impact. In the current study no age effects were evident in the normal or abnormal categories across test procedures. Subjects were between 18 and 38 years of age in the normally hearing group, and between 12 and 21 years of age in the experimental group.

The third and most likely contributory factor is offered by Picton and colleagues, namely, the influence of recruitment and the concomitant presence of abnormal tuning curves. In order to evaluate this possibility, the characteristics and pathology of recruitment should be considered in greater detail.

Loudness recruitment is defined as abnormally rapid growth of loudness with increases in stimulus intensity (Hallpike & Hood, 1960), creating a significant shrinking of dynamic range (area between threshold and levels of loudness discomfort). Inversely, it refers to responses attaining recognition at closer intensities to threshold than in normally functioning ears (Picton et al., 1998). Historically abnormal loudness growth has been attributed to an abnormal increase in firing rate once the neural threshold of the damaged cochlea was exceeded (Henderson et al., 1994). Salvi et al. (1983a,b) tested the hypothesis of discharge-rate levels from a large sample of auditory fibers obtained from chinchillas that were subjected to noise exposure of 95 dB SPL in the 0.5 kHz region for five days. Threshold elevations of 30-60 dB were recorded in comparison to baseline threshold data of animals that have not been exposed to the noise. The significant threshold shift did not alter the discharge rate-level functions. Kiang et al. (1970) as well as Harris & Dallos (1978) confirm these findings. Both studies concluded that abnormal rate level functions of single auditory fibers do not account for loudness recruitment.

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Kiang et al. (1970) and Harris & Dallos (1978) base the occurrence of loudness recruitment on the manner in which the total amount of neural activity increases with stimulus level, described as the "*rate at which new neurons are recruited into the population of neurons as intensity increases*" (Henderson et al., 1994:48). This hypothesis leans on the presence of abnormal tuning curves in the damaged cochlea (Kiang et al., 1970). The tuning curve lacks the high sensitivity tip at a particular frequency and now exhibits a similar shape to a Bekesy traveling wave, usually affecting low frequencies more than high frequencies. While the distorted tuning curves maintain their high frequency cut-off slopes (Picton et al., 1998) the use of dichotic multiple stimuli may cause interference of low frequencies with high frequencies as a result of the distorted tuning curves. While this phenomenon is present in normal cochleae at high intensities, it occurs in cases of sensorineural hearing loss close to minimum response levels (Kiang et al., 1970; Picton et al., 1998).

The use of the concept *sensorineural* when referring to recruitment is, however, opaque. There are significant differences between clinical symptoms of sensory, i.e. cochlear damage (recruitment for example) and retrocochlear pathology (Hall, 1992; Hall & Mueller, 1997). The literature does not indicate this distinction and merely differentiated between conductive middle ear pathology and sensorineural pathology. The distinction between sensory and neural needs to be drawn when discussing the possible causes of recruitment in damaged cochleae, especially because Henderson et al. (1994) offer the involvement of the central auditory pathway as another possible contributor to loudness recruitment, disrobing it as a purely cochlear phenomenon.

Recently research on animals, employing evoked potential measurements, suggests involvement of the central auditory pathway in loudness recruitment ascribed to loss of

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inhibition functions in the central pathways (Salvi et al., 1991; Henderson et al., 1994). Evoked potentials were recorded in animals following intense exposure to 2 kHz pure tone stimuli. As expected, amplitude reductions of the compound action potential as well as from recordings of the cochlear nucleus, were evident. Recordings from the inferior colliculus, however, revealed loss of sensitivity after exposure, but with an *enhancement* of the amplitude of the evoked response to extensively larger values than normal, occurring in the lower frequency regions. The alteration of the balance of excitation and inhibition in the central auditory neurons sheds light on the enhancement Salvi et al. (1991) describe units in the cochlear nucleus and inferior colliculus which have single tone inhibitory side bands surrounding the response area of a particular tuning curve, limiting the maximum discharge rates of a neuron at high intensities. Following noise exposure, these inhibitions are selectively eliminated by the trauma resulting in an increase in the firing rate of neurons evident in the larger evoked response amplitudes observed. Based on the animal model, it is, therefore, conceivable that loudness recruitment may have contributions from the central auditory pathways.

The current study limited subjects to those exhibiting clear signs of sensory hearing loss, and no additional pathology was considered. The exploration of the presence of retrocochlear nerve damage, evident in auditory neuropathy, or of complications caused by conductive pathology, is clearly indicated in subsequent clinical studies. The influence of these conditions on the accuracy of hearing prediction using Mf ASSEP has yet to be determined.

6.3.1.4.3 *The presence of spurious responses*

One of the negative consequences of automatic response detection is the consideration of noise as a signal also described as 'spurious responses' (Picton et al., 1998). This

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implies that a response is recognized by *chance,* thus defeating the whole purpose of automated response detection.

In the current study spurious responses that occurred in two of the cases will be discussed in the concluding section of the chapter. The occurrence was well within the acceptable norms as described by Picton et al. (1998), namely, that a spurious response may be expected in one in every twenty. Herdman & Stapells (2001) report three out of 120 responses to be detected by chance, while Rance, Rickards, Briggs & Cone Wesson (2001) report six out of the 368 responses to be spurious.

In order to confirm the truth of a response, Picton et al. (1998) propose greater clinical use of the phase information provided by Mf ASSEP. Responses tend to rotate clockwise, with decrease in intensity and decrease in phase delay occurring as the phase becomes smaller. At low amplitude response levels the phase information may therefore present a solution to chance detection (Dobie & Wilson, 1994) as the onset phase should be smaller than those recorded above threshold levels and in the case of spurious responses, the onset phase may be larger. Picton et al. (1998) were able to explain most of their chance responses in this manner with the exception of one instance.

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6.3.1.5 Towards pure tone threshold prediction – the result display

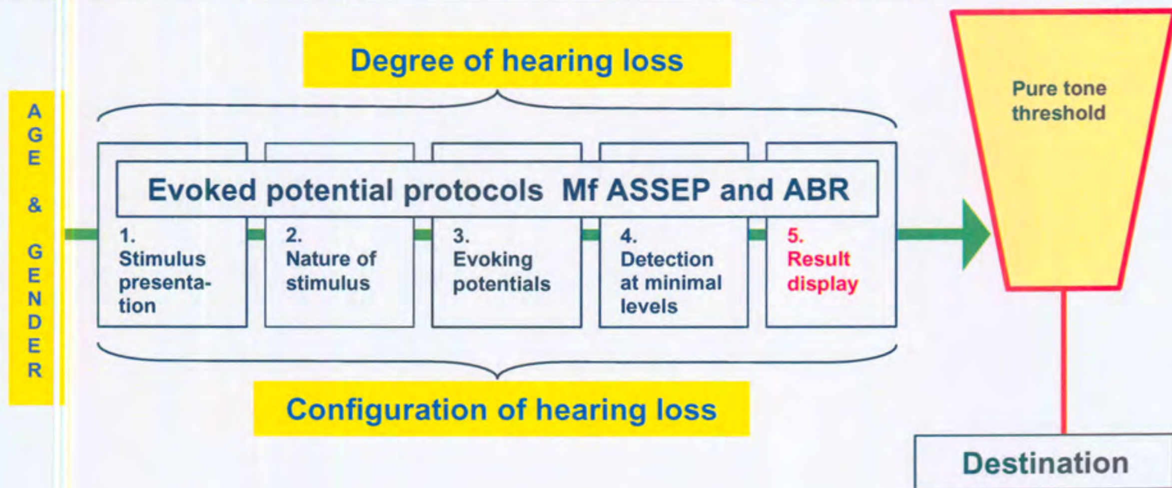

Figure 6.6 Schematic display of contributing factors to threshold prediction using Mf ASSEP and an ABR protocol.

This section concludes with a discussion of the final display of results. The pure tone results are represented in ear specific audiogram format. To date, no standardized form of display exists for evoked potential measurements. ABR levels are usually represented by a high frequency point at approximately 3 kHz, and the tone burst at 0.5 kHz, using arbitrary symbols on the same audiogram. It is possible to have tone burst threshold estimates of each frequency, if that has been performed. The introduction of standard deviation in the display is encouraged to indicate the range in which the tone burst or click approximated the pure tone threshold.

Firstly, the use of clinic specific correction factors, with specific reference to the click ABR and the Mf ASSEP should be considered. The click ABR control data showed a 16 dB correction with a standard deviation of 7, which was consistent with the literature that suggests a 10-15 dB correction factor for click ABR thresholds when pure tone

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audiometry is unavailable or unreliable (Gorga, 1999; Hall, 1992; Hood, 1998). This may have led to a slight underestimation of high frequency hearing sensitivity. The Mf ASSEP control data minimum response levels were at 33,34,32 and 30 dB HL (standard deviation of 11) at 0.5,1, 2 and 4 kHz respectively (see Table 5.1). The introduction of a correction factor may have suggested the recession of minimum response to levels well within normal limits except for 0.4 kHz namely 13,16, 17 and 26 dB for 0.5,1,2 and 4 kHz. The standard deviation of 11 does, however, provide the range for minimum response levels to indicate pathology. The use of the normative data without standard deviation is, therefore discouraged, as the underestimation of threshold and the neglect of the use of residual hearing can become a threat in difficult-to-test populations. The need for increasingly larger samples in research categories is clearly indicated in normal and pathological groupings. Moreover, the introduction of a standard deviation necessitates the use of clinic specific norms, and not only the use of existing literature data without reduplication of the complete research set-up.

The preceding discussion has dealt with the various impacting factors on the results, such as transducers, electrode placement, testing environment, patient age and calibration for example. Results obtained at threshold level are often influenced by all of these factors, and any decrease in intensity further complicates matters. The introduction of pathology on this set-up further encumbers the situation. Every care should, therefore, be taken to ensure a solid normative base to work from, using the *identica*l set-up to the research set-up, rather than over reliance on literature data without specifying differences in the methodology. Too often the methodology is not clearly documented in the data files, which further aggravates the situation.

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Although Mf ASSEP is not a test of hearing *per se*, the results can be presented as an audiogram in dB HL. Because of the nature of the stimulus and the unquestionable frequency specificity of Mf ASSEP potentials, the introduction of an audiometric format is justified, especially in difficult-to-test populations where this procedure may be the only threshold information available. It must, however, be defined as an electrophysiological audiogram to ensure differentiation from the pure tone audiogram. Because of the implications of an electrophysiological audiogram, the use of standard deviations is encouraged to ensure that that the range of the responses is taken into account and that the inferential nature of the data is reflected.

Another issue related to the display of results is the use of conversion to ensure identical psycho-acoustic parameters. There are clear differences between sound pressure level and decibel hearing level, and these two measures should not be confused. Especially when two evoked potential measurements are utilized, in particular, care should be taken to ensure comparative psycho acoustic parameters and to have these conversions clearly documented. In the current study, all results were converted to hearing level and audiometrically represented with specific symbols.

Finally, once the data have been displayed, the accuracy of the procedure in reflecting the degree and the configuration needs to be determined. In conclusion, the accuracy of the evoked potentials employed in this study can be summarized as follows:

- The click ABR did not represent the extent to which cochlear pathology affected the audiogram. While the click ABR was able to provide some insight into high frequency residual hearing, it did not address the characteristic configurations allocated in the study, nor did it reflect the overall degree of hearing loss. These findings are

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consistent with the literature (Rance et al., 1995; Hall & Mueller, 1997; Hood, 1998; Oates & Stapells, 1998; Gorga, 1999). *Because click-evoked ABRs are often insensitive to low frequency hearing impairment, alternative techniques are necessary (Hall, 1992:349).* For this reason, the use of click ABR alone is discouraged by researchers and clinicians and is well documented.

- *One option is to elicit the ABR with low frequency tone burst stimulation or toned stimuli in notched noise (Hall, 1992:349.* Tone burst was included in the current study to provide some indication of certainly the low frequency (0.5 kHz tone burst) information (Stapells, Picton, Durieux-Smith, Edwards & Moran, 1990). The combination of the click and tone burst stimuli enabled a more accurate representation of the configuration of hearing loss at a high and a low frequency point on the estimated audiogram.
- The accuracy of the Mf ASSEP minimum response levels was not affected by configuration of hearing loss and, while some minor discrepancies existed, the actual hearing curve of the data could be approximated. The Mf ASSEP was, furthermore, highly sensitive to variations in degree of hearing loss, and the minimum response levels were a close approximation of the pure tone thresholds across the frequency range.

The enquiry of this research endeavor was to determine whether the Mf ASSEP threshold estimates could translate into accurate hearing estimates when compared to pure tone audiometry and ABR protocol. The answer to this question is in the affirmative – **dichotic Mf ASSEP was able to provide accurate approximations of the degree and configuration of hearing in normal and pathological ears when compared to pure tone audiometry. Compared to the ABR protocol, more frequency specific**

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data point could be obtained, with a significant reduction in testing time and human error.

6.3 SUMMARY OF CHAPTER SIX

In this chapter, the results obtained form the control and experimental groups of the study have been interpreted and integrated into the existing body of literature on the clinical validity of Mf ASSEP as a pure tone threshold predictor. Aspects that were considered were the stimulus presentation method, the nature of the stimulus, and the technique employed to evoke the potentials from the EEG. The chapter concluded with a discussion of detection methods at minimum response levels as well as a discussion of the result display.

> ***"One of the most important features of scientific research is the detection of errors. The writer believes that positive results and failures should be discussed together. Only by such complete reporting can we get a true conception of a piece of work, of the manner of its development, and of the limitations of its principles" (von Békesy, 1960:7).***

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CHAPTER SEVEN
CONCLUSION

Aim of the Chapter

The aim of the chapter is to draw conclusions based on the study, critically assess the findings, highlight application possibilities for clinical utility and identify new questions arising from the study.

7.1 INTRODUCTION: THE PREMISES UNDERLYING THE RESEARCH PROCESS

This study consisted of two components: a literature review and an experimental component. The theoretical framework was developed as a basis for the empirical research. Based on the theoretical review, the following premises were constructed to drive the entire research process, and are summarized as follows:

1 **No single test** is able to provide an audiologist with an accurate description of hearing ability in any patient (Hall, 1992) and therefore **a test battery** approach is necessary to assess auditory function at several levels for hearing assessment (Jerger & Hayes, 1976; Hannley, 1986).

2 As an extension of the test battery, a complex test set should be performed to ensure reliable **cross-verification** or cross-check of hearing description (Hannley, 1986). Results are never accepted as conclusive proof of type, or severity of pathology unless verified by at least one additional test. These tests may be divided loosely into tests that objectively comment of influences on the ear, such as immittance and acoustic reflexes, and tests that comment on actual hearing ability, such as pure tone and speech audiometry.

3 "*The tried and tested pure tone test remains the gold standard of hearing throughout the world, and we see no replacement for it on the horizon*" (Katz:

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2002:4). The **pure tone test** is considered the most time efficient, accurate tool **to profile hearing at barely audible levels** as a function of frequency in the co-operative patient.

4. There are, however, **patients unable to co-operate** under standard testing conditions, in which case, the pure tone test, which relies heavily on patient co-operation, is rendered useless or incomplete (Balfour at al., 1998).

5. During hearing assessment of these patients, **objective testing procedures are utilized** to categorize hearing, namely, auditory evoked potentials. These tests are defined as testing procedures that require no voluntary response from the patient (Hall, 1992; Hood, 1998) and will inferentially guide a clinician to determine whether normal or abnormal function of the auditory system exists. Within these testing procedures, the test battery approach and the cross verification of results still apply.

6. **The Auditory Brainstem Response test procedure** is generally accepted as the most commonly used evoked potential technique utilized in the categorization of hearing across a frequency spectrum when conventional testing is invalid (Katz, 2002). **However, the Auditory Brainstem Response has persistent limitations,** such as incomplete knowledge about and availability of the latest masking, stimulus and filtering techniques. The ABR is considered time consuming when frequency specificity is attempted across the frequency spectrum (Weber, 1994), further aggravated by the high-level expertise requirement for software manipulation and waveform analysis (Kimura, 1985).

7. Recently, a new evoked potential technique has been described, the **Auditory Steady State Evoked Potential (ASSEP),** a continuous tone, amplitude-modulated at a frequency that provokes a SSEP at the frequency of modulation (Rickards & clark, 1984; Chambers et al., 1986). **For audiometric purposes,**

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SSEP have some advantages over ABR. The measurement is an example of true objectivity (no response is required from the patient and no interpretation is required from the researcher); frequency specific stimuli are utilized in any state of wakefulness, while results may be presented as a conventional audiogram (Lins et al., 1996).

8 The collection of ear specific threshold estimates with evoked potential techniques is **time consuming** (at least 48 tracing per subject). Lins & Picton (1995) propose the **use of multiple amplitude-modulated tones.** In this scenario, **four frequencies can be simultaneously explored in both ears** reducing the procedure to approximately eight recordings for an entire 'audiogram' (Lins & Picton, 1995; Lins et al., 1996, Perez-Abalo et al., 2001).

9 **Clinical validation has been limited** to normally hearing adults (Aoyagi et al, 1994), well babies and small numbers of hearing impaired subjects (Cohen et al., 1991; Rickards et al., 1994; Rance et al., 1998; Perez-Abalo et al., 2001).

10. **No comparison has been attempted between the SSEP and other short latency evoked potentials** that are currently used with high frequency, such as the ABR (Sininger & Cone-Wesson, 2002).

The study, therefore, attempted to determine the validity and accuracy of dichotic MF ASSEP for use in predicting hearing status in comparison to the gold standard of pure tone audiometry as well as the evoked potential standard of auditory brainstem response, in a group of normally hearing subjects and a group of adolescents with hearing loss.

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7.2 CONCLUSIONS AND EVALUATION OF THE STUDY

The results of the study will be summarized and conceptualized within the criteria for the perfect evoked potential, as described by Picton (1991). The goal in this context of threshold estimation is to obtain an audiogram that provides minimum response levels as a function of as many frequencies of the pure tone audiogram as possible (or at the very least of 0.5-4 kHz) (Picton, 1991). In order to meet this demand, an evoked potential technique should attain certain criteria (Picton, 1991). The performance of the Mf ASSEP and the ABR protocol utilized in the current study in order to meet these criteria is presented below.

Criterion 1: The AEP should provide a reasonably accurate assessment of threshold (Picton, 1991)

Within the control group:

- Mf ASSEP predicted pure tone thresholds within 26 –30 dB of the target levels across 0.5-4 kHz
- Tone burst ABR estimated the 0.5 kHz thresholds within 26 dB on average
- Click ABR, in comparison to the 1,2 and 4 kHz levels, was within 12 –13 dB.

Neither of the frequency specific measures was able to conclusively differentiate between normal hearing (0-25 dB) and mild hearing loss (26-40 dB). It can be concluded that the Mf ASSEP was as accurate as the currently used ABR technique in categorizing hearing, even with smaller standard deviations. Due to the novelty of the Mf ASSEP technique, the same consideration was not afforded to the testing parameters as evident in the large body of literature of the ABR. Three issues in particular require clinical exploration and verification:

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- The use of uniform threshold seeking procedures across test protocols (the use of 5 dB steps at MRLs in the Mf ASSEP protocol)
- Uniform acoustic environments (all testing procedures should be conducted in the same sound proof condition)
- Averaging that can be clearly specified and not arbitrarily decided based on preliminary studies.

Within the experimental group:

- Mf ASSEP predicted pure tone thresholds within 14 – 18 dB of the target levels across 0.5-4 kHz
- Tone burst ABR estimated the 0.5 kHz thresholds within 24 dB on average
- Click ABR, in comparison to the 1,2 and 4 kHz levels, was within 9 dB of the pure tone thresholds.

These findings indicate that within categories of sensory hearing loss, the use of Mf ASSEP provided accurate estimation of hearing at closer approximation than tone burst ABR, and with increased frequency specificity compared to click ABR. These findings, however encouraging in terms of the use of Mf ASSEP, cannot be generalized outside the limitations of this study. For instance, the effect of a conductive or neural component was not examined. Furthermore, the use of bone conduction in dichotic Mf ASSEP will remain a remote possibility for some time to come. The Mf ASSEP cannot substitute the unique contribution of the click ABR in site-of-lesion testing in auditory neuropathology at present (Sininger & Cone-Wesson, 2002).

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Criterion 2: Changes in subject arousal should not affect the recording of an AEP (Picton, 1991)

All protocols of the study met this criterion. The early potentials such as the ABR are quite stable during changes in arousal (Thornton et al., 1984; Picton, 1991; Hall, 1992; Hood, 1998). This was evident during the ABR protocol and also while using the MF ASSEP protocol. The current study primarily employed awake adults to ensure reliable pure tone threshold as gold standard.

Within the awake adult paradigm, the use of middle latency responses, late cortical potentials and, in particular, the 40 Hz steady state responses would be preferable as all of these potentials are more robust in adults than in children and adults would not have maturational effects to accommodate (Rickards & De Vidi, 1995; Rickards, De Vidi & McMahon, 1996). These potentials were not considered in the current study even though adults were used. Firstly, the 40Hz response was unavailable on the multiple system used in the current study. Secondly, even if it had been available, generalization and comparison to other studies would have been hampered as studies concerned with the dichotic multiple steady state in adults, particularly the work of Picton and colleagues (Lins & Picton, 1995; Lins et al., 1996; John & Picton, 2000; John et al., 2001a), only employed the 80 Hz response without exception. Thirdly, in the data collection phase of John et al. (2001a) as well as in the current study, the subjects were encouraged to relax and even fall asleep to ensure the least amount of physiological noise during recording, contra-indicating the use of middle and late latencies due to the effect of arousal on these potentials. Fourthly, the use of the 80 Hz response is further motivated by the fact that patient state could not be controlled in the current study due to the particular testing environment of the study - the researcher and equipment were separated from the sound proof booth where the subject lay. In compensation cases, particularly in industrial

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audiology, future research should explore the accuracy of these measures compared to the 40 Hz response and the late cortical responses.

Criterion 3: AEP recognition should not be influenced by age (Picton, 1991)

Age did not have an effect on either of the evoked potential protocols. This can be ascribed to the careful control of age variation in the control and experimental group between the ages of 12-38 years. Furthermore, the auditory brainstem response shows recognition at all ages, despite developmental changes in the first 18 months of life for the ABR (Hecox & Galambos, 1974). Presently ABR can currently be recorded in all age groups, with maturity and stability between 10-60 years of age (Hood, 1998). The effect of maturation on a dichotic steady state protocol has not been explored in research and is clearly indicated. Based on the findings by Rance et al. (1995), the 80 Hz monotic steady state protocol demonstrates clinical accuracy in screening and diagnosing of hearing loss in infants and young children. Similar research needs to be conducted for the multiple technique, as it would provide a novel view of the perceptive development of the human in the presence of complex stimuli other than speech. A practical concern in this regard would be to ensure that the electrode placement in the multiple technique, (usually centered around Fz, Cz and Oz) would have to reconsidered to accommodate scalp development and protection of the fontanel in infants and babies.

Criterion 4: Responses should be present at all frequencies of the pure tone audiogram (Picton, 1991)

The use of Mf ASSEP enabled the meeting of this criterion in the control as well as the experimental groups. Absent responses in this test condition were, without exception, indicative of profound hearing loss far more representatively than the ABR protocol as a result of the higher output capabilities of the Mf ASSEP equipment and the absence of

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interfering artifact. It would be prudent, however, to consider the audiogram configuration at these high intensities to reduce the risk of noise exposure in cases where the spread of residual hearing is predominantly intact in the lower or mid frequencies (Picton, 2001).

The use of tone burst ABR in the low frequency region (0.5 kHz) also met the criterion, and inferentially it can be assumed that tone burst ABR across the frequency range would rise to the task in a similar fashion. However, the limitation of maximum output in the ABR protocol limited its accuracy in the profound and even the severe condition – the high intensities required in these testing conditions caused high levels of electrical artifact, making wave detection difficult. Furthermore within the normal group and mild hearing loss category, the range of tone burst ABR MRLs were present, but not as diagnostically reliable, as these two categories had similar tone burst MRLs. As expected, the click ABR failed to meet this criterion and merely provided evidence for high frequency hearing sensitivity aided by the use of headphone transducers (Hall, 1992; Hood, 1998).

Criterion 5: The perfect AEP should measure response levels that are specific to different frequencies on the audiogram (Picton, 1991)

The use of the Mf ASSEP technique offered frequency-specific response levels, as clearly evident in the accurate translation of pure tone threshold within the various manipulations of audiogram configuration in the experimental group of the study.

The tone burst was more frequency specific, although the spread of energy to adjacent frequencies, the latency jitter evident, low frequency responses at high intensities, as well as the brevity of the stimulus as such, reduced the specificity when compared to a

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pure tone threshold at 0.5 kHz (Lins & Picton, 1995). Click ABR, however, did not provide frequency-specific results (Starr, 1998).

In summary, it can be concluded that the Mf ASSEP is able to meet all clinical criteria as proposed by Picton (1991). However, in a clinical context, two issues, additional to those proposed by Picton (1991), need to be considered in order to provide an audiologist with an optimally functioning assessment tool in difficult-to-test populations.

In a clinical context, the criteria for the 'perfect' evoked potential should be augmented to include two additional parameters:

Additional criterion: The perfect AEP should provide clinicians with sufficient diagnostic information within a clinically viable time frame as specified by the work setting.

The ABR time frame did not include waveform analysis. Within the control group, therefore, the use of Mf ASSEP enabled the collection of more frequency specific information in a shorter period, without the additional burden of subjective waveform analysis. In the experimental group, more data could be collected within 30 minutes with Mf ASSEP than using the ABR protocol. The Mf ASSEP is therefore able to provide sufficient diagnostic information to incur further diagnostic procedures and rehabilitation.

Additional criterion: The perfect AEP should be able to identify sites for further diagnostic investigation.

Threshold prediction should not be confused with site-of-lesion testing. The Mf ASSEP has proved to be a valuable diagnostic tool in threshold prediction, and, within the limitations of the study, indicative of an improvement over the existing ABR protocol.

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Currently, its role in site-of-lesion testing is surpassed by the clinical utility of a click ABR. As Burkard & Secor (2002:234) state: *the ABR is useful for differentiating conductive, sensory-neural and retrocochlear disorders*". It still provides a relatively inexpensive alternative to MRI in the early stages of the diagnostic regimen. Particularly in the description of unusual auditory findings, the clinical utility of the ABR is high.

An example of this application is observed in the assessment of auditory neuropathy (AN) as described by Starr et al. (1996) and Hood (1998). Subjects presenting with this affliction often exhibit:

- Absent or abnormal ABR's;
- in the presence of normal cochlear functioning as measured by OAE or Cochlear Microphonic;
- absent acoustic reflexes; and
- speech recognition scores poorer than predicted from the pure tone threshold levels.

The diagnosis of this phenomenon is primarily based on the results obtained using several different evoked potential techniques (OAE, ABR and the like) as *measures of function* and not on diagnostic *imaging procedures* (Burkard & Secor, 2002, emphasis mine).

The increasing emergence of descriptions of AN brings to the surface some questions about the compounding of site-of-lesion as either conductive or **sensorineural**. The difficulty with **sensorineural** is created by the amalgamation of two critically different impairments into one, exposing diagnostic procedures to misinterpretation (Katz, 2002). Katz (2002:8) states, "*often when a referral source sees that the person has a*

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sensorineural loss, he or she is relieved that it is not retrocochlear. It surely could be. "We recommend a return to the term sensory-neural, or for even greater clarity, sensory/neural."

While this suggestion seems viable, it must be noticed that within the same text, in a later chapter, Burkard & Secor (2002) can be quoted refuting Katz's exact point by differentiating between sensory-neural and retrocochlear, even though the hyphenated form was used. When diagnosing auditory neuropathy Starr (1998:35) states that "*the concept of sensorineural hearing loss can now be disentangled into sensory hearing loss or a neural hearing loss. We will need to develop methods to parcel out the relative contributions to the disorder of the two processes (sensory versus neural)".*

The click ABR is in the unique position of assisting the disentangling of symptoms and providing differential diagnostic site-of-lesion information in all subjects who present with unusual standard audiometric findings. The Mf ASSEP, at this moment in time, fails this critical criterion of a perfect evoked potential because of its inability to provide clinicians with site-of-lesion information, and hence cannot be performed alone. However, it must be considered that the body of literature of scientific clinical knowledge on dichotic Mf ASSEP is still limited.

7.3 IMPLICATIONS OF THE STUDY

It cannot be disputed that audiology, which is a relatively new science with its origins in the denouement of World War II, has found its niche within the health care professions (Katz, 2002). Not only have great strides been made in terms of elevation of rehabilitative processes and education, but also in the ever increasing effectiveness of diagnostic processes to explore auditory problems. Although the common focus of the

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field has been clinical in nature and concerned with the person with hearing loss, the branches of audiology have extended to impairments like tinnitus, balance and central processing. Operating rooms, environments concerned with variations of surgical monitoring, and even courtrooms, are increasingly becoming practicing grounds for the audiologist. The education of students, other professions, employers and even communities are occurring at a steady pace. Clinical entry levels are constantly being revised and elevated and with the introduction of the Au.D the field has demonstrated that it is a vital contributor to both the medical and psycholinguistic fields of study.

Finally, audiologists are constantly involved in research endeavors to extend underlying concepts of audition and related processes. Research is undertaken to provide small but significant pieces to the puzzle of hearing. The complexity of the ear, its mechanism and composition are explored within the boundaries provided by equipment, subjects and current understanding of audition in its many forms. While most of speech recognition and discrimination necessitates supra-threshold intensity levels, most of the diagnostic research endeavors focus on barely audible levels of pure tones in an attempt to control and manipulate at least some of the multitude of variables influencing communication in real life situations.

Within the standard audiometric diagnosis, pure tones are still the cornerstone, even though the use of linguistic material (speech) remains the ultimate measure of the severity of communicative impairment in the presence of hearing loss. In other words, the function of hearing is a communicative one – to enable a listener to attend to speech. The ultimate diagnostic tool will be required to assess the total hearing mechanism with stimuli corresponding to speech sounds. In difficult-to-test populations, the paradox is somehow softened as the use of speech material and the subjective experience of the

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patient are rendered inconclusive for the applicable characteristics of insufficient co-operation (age, mental ability, physical limitations, psychological state).

This study aimed at the prediction of threshold using a new technique for application in patients unable to co-operate within the traditional testing paradigm dominated but not exclusively occupied, by the pure tone test. It is in the evoked potential realms in particular that the hand of technology has touched audiology. Objective measures have evolved from inferential measures of neural synchrony, susceptible to changes in subject state and age, into sophisticated measures of frequency specific hearing estimators applicable to subjects of all ages and stages of wakefulness. With the introduction of the Mf ASSEP, the elimination of subjectivity in waveform analysis has elevated the electrophysiological tools of hearing prediction into a truly state-of-the-art bio-technological innovation.

This study utilized two of the state-of-the-art techniques in predicting threshold, namely, dichotic Mf ASSEP and ABR. The privilege of being able to explore these exciting frontiers of diagnostic audiology places an enormous responsibility on the shoulders of researchers, not to experience a false sense of security with the sudden availability of sophisticated objective techniques, but rather to have a clearly defined understanding of the persistent limitations of the use of new techniques like Mf ASSEP in hearing prediction.

The implications of the study as a clinical tool have already been discussed. However, the final assessment of the research results can best be determined within a framework based on the words of George von Bekesy (1960:7-9) when he states: ***"When in a field of science a great deal of progress has been made and most of the pertinent***

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variables are known, a new problem may most readily be handled by trying to fit it into the existing framework. When, however, the framework is uncertain and the number of variables is large the mosaic approach is much easier".

In the scientific assessment of AEP's **most of the pertinent variables are known**. Age effects, wakefulness effects, stimulus effects, transducer effects, filters and masking options, the evoking of responses within the time and frequency domains and the variation within the normal and impaired populations have been clarified with steady exploration over 30 years, especially within the ABR protocol. The advantages and disadvantages of the ABR are, therefore, well documented.

It therefore seems to be possible to handle a new problem within the existing framework, as Von Békesy suggested. The **clinical validity of the Steady State technique** was addressed within the existing framework of the limitations of an ABR protocol during threshold prediction. Even though the two evoked potential techniques were not directly compared prior to this study (Sininger & Cone-Wesson, 2002), the literature indicates that the steady state technique is able to provide more frequency specific information, without subjective interference and in a shorter period of time. This study seemed to prove the above statement when using Mf ASSEP with normally hearing subjects as well as with subjects with sensory hearing impairment.

Caution against over generalization should be stringently applied at this juncture and **Von Bekesy's (1960) suggestion of a mosaic approach** is, therefore, valuable. The first justification for a mosaic approach is that, although most of the influencing variables on evoked potentials are known, they have not been solved or optimally accommodated in existing test protocols (Hyde, 1991). Secondly, even though a new technique such as

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the Mf ASSEP may be able to address some of the limitations in threshold prediction, the increased weight in this area may limit access to additional site-of-lesion information provided by, for example, a click ABR.

A mosaic of the Mf ASSEP is presented in Figure 7.1.

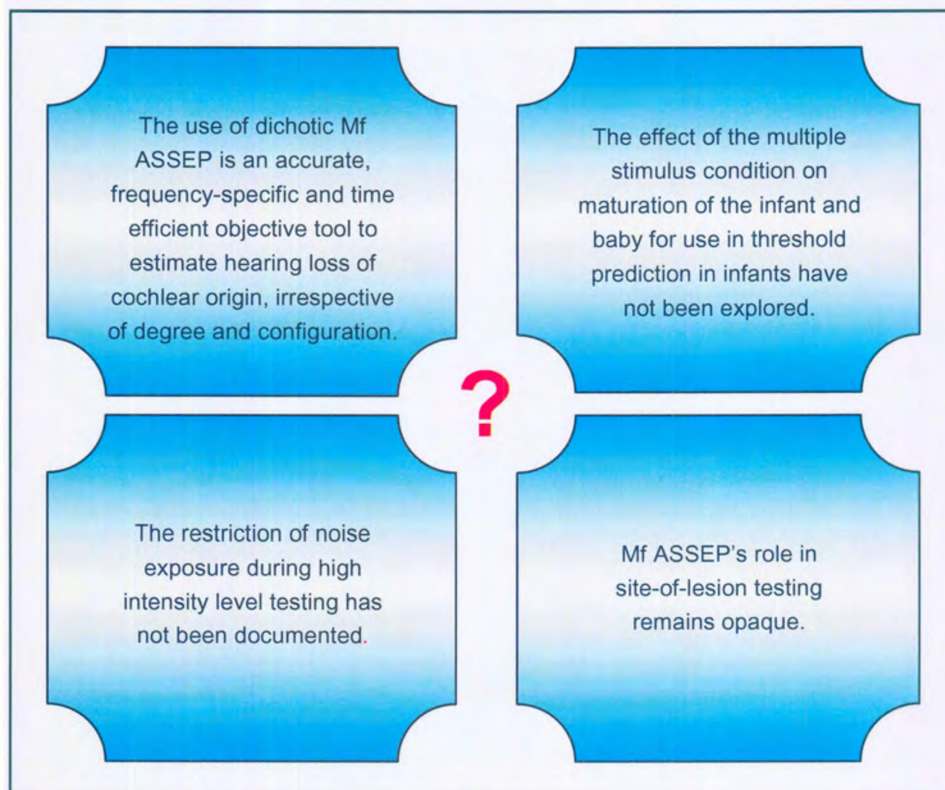

Figure 7.1. An illustration of a mosaic approach to the clinical utility of Mf ASSEP in threshold prediction

Based on the mosaic and preceding discussion, the following adjustment is foreseen in a clinical protocol for threshold estimation:

It is suggested that the Mf ASSEP technique can be utilized to predict degree and configuration of hearing loss. These findings should be crosschecked with any available

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behavioral information. However, an evoked potential crosscheck, apart from the behavioral crosscheck, is a particularly vital suggestion. To provide site-of-lesion information not obtainable form Mf ASSEP to date, other evoked potentials like OAE, Cochlear Microphonic (CM) and click ABR should be introduced on a routine basis during the electrophysiological test procedure component of diagnosis to cross-check sensory pathology (OAE and CM) and to determine neural status of a retrocochlear nature at the time of testing (Hood, 1998; Hall, 1992). Any omission in this regard could be interpreted as unaccountable service delivery and not directed at the patient's best interest.

7.4 RECOMMENDATIONS FOR FUTURE RESEARCH

7.4.1 Research aimed at enhancing clinical utility of the Mf ASSEP technique:

- The development of an assessment protocol which clearly defines the accepted ranges of averaging, and permissible noise levels within the same testing environment
- The exploration of the clinical utility of the 40 Hz response steady state technique and late cortical potentials in comparison to the 80 Hz steady state technique in the multiple condition in threshold estimation in adults
- The effect of maturation on the processing of infant and babies using complex stimuli
- The exploration of the differential diagnosing possibilities of the steady state technique in conductive pathology, neural pathology and central auditory pathology.

7.4.2 Further investigation into the use of complex stimuli in hearing prediction:

Decreases in testing time should not allow researchers to overlook some of the other critical benefits that may be gleaned from the complex nature of the stimuli. While the

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primary focus of the later development of the Mf ASSEP had been to estimate threshold in a shorter period of testing time, it is important to consider other possibilities of the multiple stimulus condition in the field of audiology. The use of this type of complex signal may be extremely useful in the attempt to predict actual hearing in cases where pathology is present. Picton et al. (1998) report the absence of a response in the multiple condition in one case, but the presence of the response in the single condition. Both these levels were above threshold. The abnormal high frequency elevated that was detected can, in fact, represent the actual hearing of the individual. They argue that the pure tone can be audible in the absence of competing signals, but the multiple ASSR can allow for the real world experience, namely, the occurrence of multiple frequencies simultaneously. What Picton and his colleagues did not comment on, however, is the inclusion of algorithms to allow for different intensity, simultaneous testing levels at different frequencies.

7.4.3 The use of Mf ASSEP as an instrument in hearing aid fitting:

The use of Mf ASSEP as a measure of functional gain can be extremely useful in pediatric hearing aid fitting. A hearing aid is ill equipped to handle rapidly changing acoustic stimuli utilizing onset responses without distortion, and the nature of the stimulus is far removed from the continuous and complex nature of speech stimuli. The regular repetition of the ASSR stimuli, which stabilizes after initial stimulation, provides constant amplitude and phase information over time at the signature carrier frequencies. The nature of the Mf ASSEP stimuli makes distortion by amplification unlikely (Regan, 1989; Picton et al., 1998).

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7.4.4 The use of Mf ASSEP and further delineation of frequency and place perception of the cochlea:

The dichotic use of multiple stimuli offers research opportunities to explore and further delineate the frequency and place analysis of sound on the basilar membrane, particularly at ever increasing intensities and also within the presence of pathology like recruitment and other forms of abnormal loudness growth. Within the clinical domain, the interactions seem not to affect the results with any significance, as was evident in the current study, however, the clinical consideration that is foremost deals with the caution that needs to be exerted when presented complex stimuli at high intensity levels. From a clinical point of view, it would be interesting to determine pure tone thresholds after exposure to Mf ASSEP within the pathological population as proposed by Picton (2001).

7.5 FINAL COMMENTS

It is vital in accountable service delivery that audiologists develop "*decision protocols that link various test procedures in a consistent and structured way*" (Hyde: 1991:25). AEPs offer a variety of procedures to accomplish this goal, and, within the context of this study, the Mf ASSEP technique offers a more accurate and time efficient method of threshold estimation across degree and configuration of sensory/neural hearing loss than the ABR protocol. It also introduces the use of complex stimuli in threshold prediction and in doing so simulates the exciting world of audition in a more representative way than clicks and tone bursts (Picton, 1991).

In clinical practice, the underlying assumption should, however, be that there is no best test for all objectives and circumstances (Picton, 1991). Thus, deliberate caution should be exercised against the pre-occupation with a single test, albeit accurate, objective and quick, as it would ultimately not be in the patient's interests. According to Hyde (1991),

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this implies that assessments ought to include more than one AEP measure instead of the indiscriminate application of a single test procedure. Hence, Mf ASSEP threshold prediction should be routinely augmented with ABR procedures for further delineation of neural influences as the "*effect of selective lesioning of the auditory pathway upon SSEPs has not been determined, nor have neuropathology variables been explored*" (Sininger & Cone-Wesson, 2002:311)

It can be concluded that the Mf ASSEP will make valuable contributions to the test battery, but it should not in any way replace the range of additional AEP procedures necessary to explore the complexities of the human ear and hearing mechanism in normally hearing and ears with hearing loss or the application of this battery in an inquiring and evaluative frame of mind. As Hyde (1991:25) states eloquently: "***Perhaps the most important thing is to be fully aware of the cause and extent of deficiencies in protocol***".

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REFERENCES

Allison, T., Wood, C.C. & Goff, W.R. 1983. Brainstem auditory, pattern-reversal visual and short-latency somatosensory evoked potentials: latencies in relation to age, sex, and brain and body size. *Electro-encephalogy Clinical Neurophysiology*, 55, 619-636.

ANSI 1996, American national standard specification for audiometers. *ANSI S3.6-1996.*

ANSI 1999, Maximum permissible ambient noise levels for audiometric test rooms, *ANSI S3.1 – 1999*

Aoyagi, M., Kiren, T., Furuse, H., Fuse, T., Suzuki, Y., Yokota, S. & Koike, Y.1994. Pure tone threshold prediction by 80Hz amplitude modulation following response. *Acta Otolaryngologica, Supplement*, 504, 7-14.

Aoyagi, M., Yamazaki, Y., Yokota, M., Fuse, T., Suzuki, Y., Ito, S. & Watanabe, T. 1996. Frequency specificity of 80 Hz amplitude modulation following response. *Acta Otolaryngologica, Supplement*, 522, 6-10.

Aoyagi, M., Suzuki, Y., Yokota, M., Furuse, H., Watanabe, T. & Ito, T. 1997. Reliability of 80 Hz amplitude modulation following response detected by phase coherence. *Audiology and Neurootology*, 4,28-37.

Arnold, S.A. 2000. The Auditory Brainstem Response. In: *Audiology Diagnosis*, R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), New York: Thieme Medical Publishers, 451-470.

© University of Pretoria

Bachman, K.R. & Hall III, J. W. 1998. Pediatric auditory brainstem response assessment: the crosscheck principle twenty years later. *Seminars in Hearing*, 19(1), 41-60.

Balfour, P.B., Pillion, J.P. & Gaskin, A. E. 1998. Distortion product emission and auditory brainstem response measures of pediatric sensorineural hearing loss with islands of normal sensitivity. *Ear and Hearing*, 20, 436-472.

Ballachanda, B.B. 1995. *The Human Ear Canal: Theoretical considerations and Clinical applications including cerumen management*. San Diego: Singular Publishing Group.

Beattie, R.C., Thielen, K.M. & Franzone, D.L. 1994. Effects of signal-to-noise ratio on the auditory brainstem response to tone bursts in notched noise and broadband noise. *Scandinavian Audiology*, 23, 47-56.

Berger, H. 1929. Uber das Elektrenkephalogram des Menschen. *Archiv fur Psychiatrie und Nervenkrankheiten*, 87, 527-570.

Block, M.G. & Wiley, T.L. 1994. Overview and basic principles of acoustic immittance measurements. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 4th edition, Baltimore: Williams & Wilkins, 271-282.

Buchwald, J.S. & Huang, C.M. 1975. Far-field acoustic response:origins in the cat. *Science*, 189, 382-384.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Burkard, R.F. & Secor, C. 2002. Overview of auditory evoked potentials. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 5th edition, Philadelphia: Lippincott, Williams & Wilkins, 233-248.

Carhart, R. & Jerger, J.F. 1959. Preferred method for determination of pure-tone thresholds. *Journal of Speech and Hearing Disorders*, 24, 330-345.

Chambers, R.D., Feth, L.L. & Burns, E.M. 1986. The relation between the human frequency-following response and the low pitch of complex tones. *Journal of the Acoustical Society of America*, 80, 1673-1680.

Chiappa, K.H.1984. Pattern-shift, visual, brainstem auditory and short latency somatosensory evoked potentials and multiple sclerosis. *Annals of the New York Academy of Sciences*, 436, 315-327.

Chiappa, K.H. & Young, R.R. 1985. Evoked Responses: overused, underused, or misused? *Archives of Neurology,* 42, 76-77.

Clark, W.A. Jr. 1958. Average Response Computer (ARC-1). *Quarterly Progress Report no. 49*, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge MA: MIT Press.

Clark, W.A., Goldstein, M.H. Jr., Brown, R.M., Molnar, C.E., O'Brien, D.F. & Zieman, H.E. 1961. The average response computer (ARC): a digital device for computing averages and amplitudes and time histograms of electrophysiological responses. *Trans IRE*, 8, 46-51.

© University of Pretoria

Cohen, L.T., Rickards, F.W. & Clark, G. 1991. A comparison of steady-state evoked potentials to modulated tones in awake and sleeping humans. *Journal of the Acoustical Society of America*, 90, 2467-2479.

Cope, Y. 1995. Objective hearing tests. In: B. McCormick (Ed.), *The medical practitioner's guide to pediatric audiology*. New York: Cambridge University Press.

Davis, P.A. 1939. The electrical response of the brain to acoustic stimuli. *American Journal of Physiology*, 126, 475-476.

Davis, H., Davis P.A., Loomis, A.L., Harvey, E.N. & Hobart, G.1939. Electrical reactions of the human brain to auditory stimulation during sleep. *Journal of Neurophysiology*, 2, 500-514.

Davis, H. & Hirsch, S.K. 1979. A slow brainstem response for low-frequency audiometry. *Audiology*, 18, 445-461.

De Waal, R. 2000. *Objective prediction of pure tone thresholds in normal adn hearing-impaired ears with distortion product otoacoustic emissions and artificial neural networks*, Unpublished D.Phil thesis, University of Pretoria, South Africa.

Dimitrijevic, A., John, M.S. & Picton, T.W. 2001. Pure tone threshold prediction in hearing impaired and normal hearing adults using master (Multiple Auditory Steady State Evoked Responses). Oral Presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

© University of Pretoria

Dobie, R.A. & Wilson, M.J. 1994. Phase weighting: a method to improve objective detection of steady-state evoked potentials. *Hearing Research*, 79,94-98.

Dolphin, W.F. & Mountain, D.C. 1993. The envelope following response: scalp potentials elicited in the mongolian gerbil using sinusoidally AM acoustic signals. *Hearing Research*, 58, 70-78.

Don, M., Eggermont, J.J. & Brackman, D.E. 1979. Reconstruction of the audiogram using brainstem responses and high pass noise masking. *Annals of Otology, Rhinology and Laryngology Supplement*, 57, 1-20.

Eggermont, J.J. 1991. Peer commentary on: Clinical usefulness of auditory evoked potentials: A critical evaluation. *JSLPA*, 15(9), 19-25.

Elberling, C. & Don, M. 1987. Threshold characteristics of the human auditory brain stem response. *Journal of the Acoustical Society of America*, 81, 115-121.

Ferraro, J.A. & Durrant, J.D. 1994. Auditory Evoked Potentials: Overview and Basic Principles. In: J Katz (Ed.), *Handbook of Clinical Audiology*, 4th edition, London:Williams & Wilkins, 317-338.

Frank, T. 2000. Basic Instrumentation and Calibration. In: R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), *Audiology Diagnosis*, New York: Thieme medical Publishers, 181-225.

© University of Pretoria

Galambos, R., Makeig, S. & Talmachoff, P.J. 1981. A 40Hz auditory potential recorded from the human scalp. *Proceedings of the National Academy of the Sciences*, 78, 2643-2647.

Goldstein, R. & Aldrich, W.M. 1999. *Evoked Potential Audiometry: Fundamentals and Applications.* Boston: Allyn & Bacon.

Goodman, A. 1965. Reference zero levels for pure-tone audiometer. *ASHA*, 7, 262-263.

Gorga, M.P. & Worthington, D.W. 1983. Some issues relevant to the measurement of frequency specific auditory brainstem responses. *Ear and Hearing*, 4, 353-362.

Gorga, M.P., Beauchaine, K.A., Reiland, J.K., Worthington, D.W. & Javel, E. 1984. Effects of stimulus duration of ABR thresholds and on behavioral thresholds. *Journal of the Acoustical Society of America*, 76, 616 – 619.

Gorga, M.P. & Abbas, P.J. & Worthington, D.W. 1985. Stimulus calibration in ABR measurements. In J.T. Jacobson (Ed.), *The Auditory Brainstem Response*. San Diego: College-Hill Press, 49-64.

Gorga, M.P., Kaminski, J.R., Beauchaine, K.L. & Bergman, B.M. 1993. A comparison of Auditory Brainstem Response thresholds and latencies elicited by air- and bone-conducted stimuli. *Ear & Hearing*, 14(2), 85-94.

Gorga, M.P. 1999. Predicting auditory sensitivity from Auditory Brainstem Response measurements. *Seminars in Hearing*, 20(1), 29-43.

© University of Pretoria

Hall III, J.W. & Ruth, R.A 1985. Acoustic reflexes and auditory evoked responses in hearing aid selection. *Seminars in Hearing*,6,251-277.

Hall III, J.W. 1992. *Handbook of Auditory Evoked Responses.* Boston: Allyn & Bacon.

Hall III, J.W. & Chandler, D. 1994. Tympanometry. In:J. Katz (Ed.), *Handbook of Clinical Audiology,* 4th edition. London: Williams & Wilkins, 283-299.

Hall III, J.W. & Mueller, H. G. 1997. *Audiologists' Desk Reference Volume 1, Diagnostic Audiology Principles, Procedures, and Practice.* San Diego: Singular Publishing Group.

Hall III, J.W. 2000. *Handbook of Otoacoustic Emissions*. San Diego: Singular Publishing Group.

Hall III, J.W. 2001. *Otoacoustic emissions and Auditory Evoked Response Hands-on Workshop.* 19-21st June, Sponsored by Department of Communicative Disorders, University of Florida, Gainsville, Florida, USA.

Hall III, J.W. 19 June 2001. Personal communication, University of Florida.

Halliday, M. 1993. *Evoked potentials in clinical testing*, 2nd edition. London: Churchill Livingstone.

Hallpike, C.S. & Hood, J.D. 1960. Observations on the neurological mechanism of the loudness recruitment phenomenon. *Acta Otolaryngology*, 50, 472-486.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Hannley, M. 1986. *Basic principles of auditory assessment*. San Diego:College-Hill Press.

Harris, D & Dallos, P. 1978. Properties of auditory nerve responses in the absence of outer hair cells. *Journal of Neurophysiology*, 41, 365-383.

Hawkins, D. & Haskell, G. 1982. A comparison of functional gain and 2 cubic centimeter coupler gain. *Journal of Speech and Hearing Disorders*, 47,71-76.

Hecox, K. & Galambos, R. 1974. Brainstem auditory evoked response in human infants and adults. *Archives of Otolaryngology*, 99, 30-33.

Henderson, D., Salvi, R.J., Boettcher, F.A. & Clock, A.E. 1994. Neurophysiologic correlates of sensory-neural hearing loss. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 4th edition. London: Williams & Wilkins, 37-56.

Herdman, A.T., Lins, O., van Roon, P., Stapells, D.R., Scherg, M. & Picton, T.W. 2001. Generators of the auditory steady state responses. Oral presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study group (IERASG)*, Vancouver, Canada.

Herdman, A.T., Picton, T.W., & Stapells, D.R. 2001. Place specificity of auditory steady state responses. Poster presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

© University of Pretoria

Herdman, A.T. & Stapells, D.R. 2001. Thresholds determined using monotic and dichotic multiple auditory steady state response technique in normal hearing subjects. *Scandinavian Audiology*, 30(1), 41-49.

Herrman & Thornton 1991. Peer commentary on: Clinical usefulness of auditory evoked potentials: A critical evaluation. *JSLPA*, 15(9), 19-25.

Hood, L..J. 1995. Estimating auditory function with auditory evoked potentials. *Hearing Journal*, 48(10), 32-42.

Hood, L.J.1998. *Clinical applications of the auditory brainstem response*. San Diego: Singular publishing Group.

Hood, L.J. 24 June 2001. Personal Communication, 17[Th] Biannual International Evoked Response Study Group, University of British Columbia.

Hughson, W. & Westlake, H. 1944. Manual for program outline for rehabilitation of aural casualties both military and civilian. *Transdisciplinary American Academy of Ophthalmology and Otolaryngology, Supplement.* 48, 1-15.

Hyde, M.L., Riko, K. & Malizia, K. 1990. Audiomertic accuracy of the click ABR in infants at risk for hearing loss. *Journal of the American Academy of Audiology*,1, 59-66.

Hyde, M. 1991. Peer commentary on: Clinical usefulness of auditory evoked potentials: A critical evaluation. *JSLPA,* 15(9), 19-25.

© University of Pretoria

Jerger, J. & Hayes, D.1976. The crosscheck principle in pediatric audiometry, reprinted from the Journal of Otolaringology October 1976, 102. In: B. Alford & S. Jerger (Eds.), *Clinical Audiology, the Jerger perspective* (1993), San Diego: Singular Publishing Group, 59-65.

Jerger, J. 1993. The Jerger perspective. In: B. Alford & S. Jerger (Eds.), *Clinical Audiology, the Jerger perspective*. San Diego: Singular Publishing Group, 59-65.

Jerger, J. 1998. The Auditory Steady State Response. *Journal of the American Academy of Audiology*, 9(5), Editorial.

Jerger, J.F., Grimes, A.M., Jacobson, G.P., Allbright, K.A. & Moncrieff, D.2000. The future of diagnostic audiology. In: R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), *Audiology Diagnosis.* New York: Thieme Medical Publishers, 615-626.

Jewett, D.L. 1970. Volume conducted potentials in response to auditory signals as detected by averaging in a cat. *Electroencephalography and Clinical Neurophysiology*, 28, 609-618.

Jewett, D. and Williston, J.1971. Auditory evoked far fields averaged from the scalp of humans. *Brain,* 94,681-696.

John, M.S., Lins,O.G., Boucher, B.L. & Picton,T.W. 1998. Multiple Auditory Steady-State Responses (MASTER): stimulus and recording parameters. *Audiology*, 37, 59-82.

© University of Pretoria

John, M.S. & Picton, T.W. 2000. Human auditory steady state responses to amplitude-modulated tones: phase and latency measurements. *Hearing Research*,141, 57-79.

John, M.S., Dimitrijevic, A. & Picton,T.W. 2001a. Weighted averaging of steady state responses. *Clinical Neurophysiology*, 112, 555-562.

John, M.S., Dimitrijevic, A., van Roon,P. & Picton,T.W. 2001b. Multiple auditory steady state responses to AM and FM stimuli. *Audiology and Neuro-Otology*,6,12-27.

Johnson, T.A. & Brown, C.J.2001. Preliminary results using the ERA device to measure auditory steady-state response thresholds: comparing audiometric, ASSR and ABR thresholds in adults. Poster presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

Johnston, J.M. & Pennypacker, H.S. 1993. *Strategies and Tactics of Behavioral Research.* New Jersey: Lawrence Erlbaum Associates.

Joint Committee of Infant Hearing. 1994 Position statement. *ASHA*, 36, 38-42.

Katz, J. 1994. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 4th edition, London: Williams & Wilkins, 3-5.

Katz, J. 2002. Clinical Audiology. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 5th edition. London: Williams & Wilkins, 3-8.

© University of Pretoria

Kemp. D.T. 1979. Evidence of mechanical nonlinearity and frequency selective wave amplification in the cochlea. *Archives of Otorhinolaryngology*, 224, 37-45.

Kiang, N.Y., Liberman, M. C.& Levine R.A. 1970. Auditory-nerve activity in cats exposed to ototoxic drugs and high-intensity sounds. *Annals of Otology, Rhinology and Laryngology*, Nov-Dec, 85,752-68.

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

Kileny, P.R. & Magathan, M.G. 1987. Predictive value of ABR in infants and children with moderate to profound hearing impairment. *Ear and Hearing*, 8, 217-221.

Kimura, J.1985. Abuse and misuse of evoked potentials as a diagnostic tool. *Archives of Neurology*, 42, 78-80.

Kraus, N., Smith, D. Reed, N. Stein, L & Cartree, C. 1985. Auditory middle latency responses in children: effects of age and diagnostic category. *Electroencephalography and clinical Neurophysiology*, 62,343-351.

Kurtzberg, D. 1989. Cortical event-related potential assessment of auditory system function. *Seminars in Hearing*, 10, 252-260.

Kuwada,S., Batra, R. & Maher, V.L. 1986. Scalp potentials of normal and hearing-impaired subjects in response to sinusoidally amplitude-modulated tones. *Hearing Research*, 21:179-192.

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YUNIBESITHI YA PRETORIA

Luterman, D. 1986. A perspective on clinical and teaching interaction. In: D. Luterman (Ed.), *Deafness in Perspective.* San Diego: College-Hill Press, 193-200.

Margolis, R.H. & Hunter, L.H. 2000. Acoustic Immittance Measurements. In R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), *Audiology Diagnosis.* New York: Thieme, 381-425.

Martin, F.N. 1986. Audiology in Perspective. In: D. Luterman (Ed.), *Deafness in Perspective.* San Diego:College-Hill Press,15-35.

Mens, L.H.M., Gelders,E., Van Eeghem, P., van der Reijden, C.H., Snik, A. & Wouters, J. 2000. Frequency specific objective audiometry with multiple frequency amplitude modulation following response (MF-AMFR). Oral presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

Moore, E.J.1993. *Bases for Auditory Brainstem Evoked Responses.* New York:Grune & Stratton.

Moushegian, G., Rupert, A.L. & Stillman, R.D. 1973. Scalp-recorded early response in man to frequencies in the speech range. *Electroencephalography and Clinical Neurophysiology*, 35, 665-667.

Mühler, R., Pethe, J. & von Specht, H. 2001. Residual background noise in steady state response recordings. Oral presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG),* Vancouver, Canada.

© University of Pretoria

Neuman, W.L. 1997. *Social Research Methods: Qualitative and Quantative Approaches, 3rd edition*. Boston: Allyn and Bacon.

National Institutes of Health Consensus Committee, 1993. Early identification of hearing impairment in infants and young children, *NIH consensus statement*, 11, 1-24.

Northern, J.R. & Downs, M.P.1991. *Hearing in children*. Philadelphia: Lippincott, Williams & Wilkins.

Norton, S. 1993. Application of transient evoked otoacoustic emissions to pediatric populations. *Ear and Hearing*, 14, 64-74.

Oates, P. & Stapells, D.R. 1998. Auditory Brainstem response estimates of the pure-tone audiogram: current status. *Seminars in hearing*, 19(1), 61-85.

Osterhammel, P.A., Shallop, J.K.& Terdilksen, K. 1985. The effect of sleep on the auditory brainstem response (ABR) and the middle latency response (MLR). *Scandinavian Audiology*, 14, 47-50.

Pantev,C., Roberts, L.E., Elbert, T., Rob, B & Wienbruch, C. 1996. Tonotopic organization of the sources of human auditory steady-state responses, *Hearing Research*, 101,62-74.

Perez-Abalo, M.C., Savio, G., Torres, A., Martin, V., Rodriguez, E. & Galan, L. 2001. Steady state responses to multiple amplitude modulated tones: an optimized method to test frequency specific thresholds in hearing impaired children and normal subjects. *Ear and Hearing*, 22(3), 200-211.

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UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Perez-Abalo, M.C. 19 February 2001. Personal communication, University of Pretoria.

Picton, T.W., Skinner, C.R., Champagne, S.C., Kellet, A.J.C. & Maiste, A.C. 1987. Potentials evoked by the sinusoidal modulation of the amplitude or frequency of tone. *Journal of the Acoustical Society of America*, 82, 165 - 178

Picton,T.W. 1991. Clinical usefulness of auditory evoked potentials: A critical evaluation, *JSLPA*, 15(9), 3-18.

Picton, T.W., Durieux-Smith, A., Champagne, S., Whittingham, J., Moran, L., Giguére, C. & Beauregard, Y. 1998. Objective evaluation of aided thresholds using auditory steady-state responses. *Journal of the American Academy of Audiology*, 9, 315-331.

Picton, T.W. 2001. Current status of auditory steady-state responses: A view from IERASG 2001 presentations. Oral presentation, *17th Biennial Symposium, International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

Plourde, G.& Picton, T.W. 1990. Human auditory steady state response during general anesthesia. *Anesthesia Analgesics*, 71, 460-468.

Pratt, H. & Sohmer, H. 1978. Comparison of hearing threshold determined by auditory pathway electric responses and by behavioral responses. *Audiology*, 17, 285-292.

Rance, G., Rickards, F.W., Cohen, L.T., Burton, M.J. & Clark, G.M. 1993. Steady state evoked potentials: a new tool for the accurate assessment of hearing in cochlear candidate implant candidates. Advances in Otorhinolaryngology, 48, 44-48.

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Rance, G., Rickards, F.W., Cohen, L.T., De Vidi, S. & Clark, G. 1995. The automated prediction of hearing thresholds in sleeping subjects using auditory steady-state evoked potentials. *Ear and Hearing*, 16, 499-507.

Rance, G., Dowell, R.C., Rickards, F.W., Beer, D.E. & Clark, G.M. 1998. Steady State evoked potential and behavioral hearing thresholds in a group of children with absent click evoked auditory brainstem response. *Ear and Hearing*, 19, 48-61.

Rance, G., Rickards, F.W., Briggs, R. & Cone Wesson, B. 2001. Assessment of hearing in infants with moderate-profound impairment: the University of Melbourne experience with steady-state evoked potential testing. Oral presentation, 17th Biennial Symposium, *International Evoked Response Audiometry Study Group (IERASG)*, Vancouver, Canada.

Regan, D. & Cartwright, R.F. 1970. A method of measuring the potentials evoked by simultaneous stimulation of different retinal regions. *Electroencephalography and Clinical Neurophysiology*, 28, 314-319.

Regan, D.1982. Comparison of transient and steady –state methods. *Annals of the New York Academy of Science*, 45-71.

Regan, M.P. & Regan, D. 1993. Non-linear terms produced by passing amplitude-modulated sinusoids through hair cell transduction function. *Biology and Cybernetics*, 69, 439-446.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Regan, D.1989. *Human Brain Electrophysiology: Evoked Potentials and Evoked Magnetic Fields in Science and Medicine*. New York: Elsevier.

Rickards, F.W. & Clark, G. 1984. Steady State Evoked Potentials to amplitude-modulated tones. In: R.H. Nodar & C. Barber (Eds.), *Evoked Potentials II*, Boston: Butterworth, 163-168.

Rickards, F.W., Tan, L.E., Cohen, L.T., Wilson, O.J., Drew, J.H. & Clark, G.1994. Auditory steady state evoked potentials in newborns. *British Journal of Audiology*, 28, 327-337.

Rickards, F.W. & De Vidi, S. 1995. Exaggerated hearing loss in noise induced hearing loss compensation claims in Victoria. *The medical Journal of Australia*, 163, 360-363.

Rickards, F.W., De Vidi, S. & McMahon, D.S. 1996 Cortical evoked response audiometry in noise induced hearing loss claims. *Australian Journal of Otolaryngology,* 2(3), 237-241.

Rickards, F.W. 25 March 2002. Personal communication, University of Melbourne

Robbinette, M.S.1994. Integrating audiometric results. In: J. Katz (Ed.), *Handbook of Clinical Audiology*, 4th edition. Baltimore: Williams & Wilkins.

Roeser, R.J., Buckley, K.A. & Stickney, G.S. 2000. Pure tone tests. In: R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), *Audiology Diagnosis*, New York: Thieme Medical Publishers, 227-252.

© University of Pretoria

Roeser, R.J., Valente, M. & Hosford-Dunn, H. 2000. Diagnostic procedures in the profession of Audiology, In: R.J. Roeser, M. Valente & H. Hosford-Dunn (Eds.), *Audiology Diagnosis*. New York: Thieme Medical Publishers, 1-18.

Ross, M.1986. A perspective on amplification: Then and now. In: D. Luterman (Ed.), *Deafness in Perspective*. San Diego: College --Hill Press, 35-55.

Salvi, R.J., Henderson, D., Hamernik, R. & Ahroon, W.A.1983a. Neural correlates of sensorineural hearing loss. *Ear and Hearing*, 4,115-129.

Salvi, R.J., Henderson & Hamernik, R. 1983b. Physiological basis for sensorineural hearing loss. In J.V. Tobias & E.D. Schubert (Eds.), *Hearing Research and Theory, Volume 2*, New York: Academic Press.

Salvi, R.J., Powers, N.L., Saunders, S.S., Boettcher, F.A. & Clock, A.E. 1991.Enhancement of evoked response amplitude and single unit activity after noise exposure. In: A. Dancer, D. Henderson, R.J. Salvi & R.P. Hamernik (Eds.), *Effects of noise on the auditory system*. Toronto: BD Decker, 42-68.

Seewald, R.C., Ross, M. & Spiro, M.K. 1985. Selecting amplification characteristics for young hearing-impaired children. *Ear and Hearing*, 6, 48-53.

Selters, W.A. & Brackman, D.E. 1977. Acoustic tumor detection with brain stem electric response audiometry. *Archives of Otolaryngology*, 103, 181-187.

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Sininger, Y.S. & Cone-Wesson,B. 2002 Threshold prediction using auditory brainstem response and steady state evoked potentials with infants and young children. In : J. Katz (Ed.),. *Handbook of Clinical Audiology, 5th edition*, Philadelphia: Lippincott, Williams & Wilkins, 298-323.

Smit, G.J.1983. *Navorsingsmetodes in die gedragswetenskappe.* Pretoria: Haum opvoedkundige uitgewers.

Sohmer, H. and Feinmesser,M. 1967. Cochlear action potentials recorded from the external ear in man. *Annals of Otology, Rhinology and Laryngology*, 76, 427-438.

Sohmer, H. & Kinarti, R. 1984. Survey of attempts to use auditory evoked potentials to obtain an audiogram. *British Journal of Audiology*, 18, 237-244.

Stach, B.A. 1998. *Clinical Audiology: An introduction.* San Diego: Singular Publishing Group.

Stapells, D.R. & Picton, T.W. 1981. Technical aspects of brainstem evoked potential audiometry using tones. *Ear and Hearing*, 2, 20-29.

Stapells, D.R.1984. *Studies in evoked potential audiometry.* Unpublished Ph.D dissertation, University of Ottowa, Ontario.

Stapells, D.R., Picton, T.W., Perez-Abalo, M.C., & Smith, A. 1985. Frequency specificity in evoked potetial audiometry. In T.J. Jacobson (Ed.), *The Auditory Brainstem Response.* San Diego: Colege Hill Press, 147-177.

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YUNIBESITHI YA PRETORIA

Stapells, D.R., Galambos, R., Costello, J. & Makeig, S. 1988. Inconsistency of auditory middle latency and steady state responses in children. *Electroencephalography and clinical Neurophysiology*, 71, 289-295.

Stapells, D.R.1989. Auditory brainstem response assessment of infants and children. *Seminars in Hearing*, 10, 229-251.

Stapells,D.R., Picton, T.W., Durieux-Smith, A., Edwards, C.G. & Moran, L.M. 1990. Thresholds for short-latency auditory evoked potentials to tones in notched noise from infants and young children with normal hearing and hearing impaired subjects. *Audiology,* 29, 262–274.

Stapells, D.R.1994. Low frequency hearing and the auditory brainstem response. *American Journal of Audiology*, 3, 11-13.

Stapells, D.R., Gravel, J. & Martin, B.A. 1995. Thresholds for auditory brainstem responses to tones in notched noise from infants and young children with normal hearing and sensorineural hearing loss. *Ear and Hearing*, 16, 361-371.

Stapells, D.R. & So, M.R. 1999. High pass noise masking / derived-band auditory brainstem responses: cochlear contributions determined by narrow band maskers, oral presentation, *16th Biennial International Evoked Response Study Group (IERASG),* Tromso, Norway.

Starr, A.1977. Auditory brain-stem responses in brain death. *Brain*, 99, 543-554.

© University of Pretoria

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YUNIBESITHI YA PRETORIA

Starr, A., Picton, T.W., Sininger, Y., Hood, L.F. & Berlin, C.W. 1996. Auditory Neuropathy. *Brain*, 119, 741-753.

Starr, A.1998. A neurologist's view of auditory brainstem potentials. *Seminars in Hearing*, 19(1), 29-37.

Strachan, A. 2001 *Die effek van skadelike geraasvlakke, hetsy chronies of eenmalig, op die vestibulêre stelsel van die mens*. Unpublished Undergraduate Research Report, University of Pretoria, South Africa.

Teas, D.C., Eldredge, D.H. & Davis, H. 1962. Cochlear responses to acoustic transients: an interpretation of whole-nerve action potentials. *Journal of the Acoustical Society of America*, 34, 1438-1459.

Thornton, A.R. & Abbas, P.J. 1980. Low-frequency hearing loss: perception of filtered speech, psychophysical tuning curves, and masking. *Journal of the Acoustical Society of America*, 67, 638-643.

Thornton, C., Heneghan, C.P.H., James, M.F.M. & Jones, J.G.1984. The effects of halothane and enflurane anesthesia on the early auditory evoked potentials in humans. In R.H. Nodar & C. Barber (Eds.), *Evoked Potentials II: The second International Evoked Potentials Symposium* , Boston: Butterworth, 483-489.

Tooth, G. 1947. On the use of mental tests for the measurement of disability after head injury: With a comparison of results between these tests in patients after head injury and psychoneurotics. *Journal of Neurology, Neurosurgery and Psychiatry*, 10, 467-471.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Valdes, J.L., Perez-Abalo, M.C., Martin, V., Savio, G., Sierra, C. Rodriques, E. & Lins, O. 1997. Comparison of statistical indicators for the automatic detection of 80Hz auditory steady state responses. *Ear and Hearing*, 18(5), 420-429.

Viemeister, N.F. & Wakefield, G.H.1991. Temporal integration and multiple looks, *Journal of the Acoustical Society of America*, 90, 858 – 865.

Von Békesy, G. 1960. *Experiments in Hearing*. New York:McGraw-Hill.

Von Helmholtz, H.L.F. 1863. *Die Lehre von dem Tonempfindungen als psichologische Grundlage fur die Theorie der Musik*. Brunswick: Vieweg-Verlag.

Waterson, J. 2001. Balancing Action and Research: Reflections on Action Research Project in a Social Services Department. In: C.J. Finer & G.L. Hundt (Eds.), *The business of research Issues of Policy and Practice*, Oxford: Blackwell Publishers Inc., 140-156.

Weber, B.1994. Auditory Brainstem response: threshold estimation and auditory screening. In: J.Katz (Ed.), *Handbook of Clinical Audiology, 4th edition*, Baltimore: Williams & Wilkins, 375-386.

Wei, W.W.S. 1990. Estimation of the spectrum. In *Time series Analysis: Univariate and Multivariate methods*. Addison-Wesley: Redwoord City, 256-287.

White, K.R. & Behrens, T.R. 1993. The Rhode Island Hearing Assessment Project: Implications for universal newborn screening. *Seminars in Hearing*, 14, 1-119.

© University of Pretoria

UNIVERSITEIT VAN PRETORIA
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YUNIBESITHI YA PRETORIA

Wilson,W. 2000. A basic, introductory guide to recording auditory evoked potentials. *SASLHA seminar and workshop on AEP's and the assessment of CAPD*, Johannesburg, South Africa.

Zurek, P.M. 1992. Detectability of transient and sinusoidal otoacoustic emissions. *Ear and Hearing*, 13, 307-310.

Zwislocki, J. 1960. Theory of temporal auditory summation. *Journal of the Acoutical Society of America*, 32,1046-1060.

Zwislocki, J.J. 1991. What is the cochlear place code for pitch? *Acta Laryngology*, 111,256-262.

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APPENDICES

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Appendix A: Data sheet for normal ears and ears with hearing loss

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Data from the group with normal hearing

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Case	Age	Gender	Ear	BTR				SSR				ABR-TB	ABR-Clic	Testing time		
				0.5kH	1kHz	2kHz	4kHz	0.5kHz	1kHz	2kHz	4kHz	0.5kHz	2-4kHz	PT	SSR	ABR
			1	10	15	15	20	40	30	30	20	40	30			
1	31.1	1	2	10	15	15	15	40	30	20	20	30	20	17	25	54
			1	0	0	0	0	50	30	20	30	40	10			
2	18.5	2	2	5	5	5	0	30	30	20	30	10	10	17	25	28
			1	25	25	10	0	40	40	20	40	60	30			
4	22.74	1	2	5	0	5	0	20	30	20	30	20	10	17	32	37
			1	5	0	5	10	40	40	50	40	30	30			
5	29.12	1	2	5	0	10	5	40	40	40	50	30	30	17	22	24
			1	0	0	0	0	10	20	30	20	40	10			
6	26.42	2	2	0	0	0	0	10	30	20	10	40	5	17	21	19
			1	0	0	10	15	40	30	30	30	30	20			
7	20.04	1	2	5	0	0	0	30	20	20	30	20	20	17	24	16
			1	0	0	0	0	20	20	20	30	10	10			
8	21.79	2	2	0	0	0	0	20	20	20	30	20	20	17	25	23
			1	15	0	10	10	30	50	30	10	20	20			
10	27.36	1	2	0	0	10	5	20	30	30	10	20	20	17	29	22
			1	0	0	0	0	30	20	30	30	10	10			
11	20.67	2	2	0	0	0	0	50	50	50	30	40	10	17	17	20
			1	0	0	0	0	30	20	50	30	40	15			
12	25.54	2	2	0	0	0	0	20	30	50	40	10	20	17	27	22
			1	5	0	0	0	30	30	10	10	10	10			
13	22.92	1	2	0	5	5	5	30	10	20	20	10	20	17	14	22
			1	0	0	5	10	30	30	20	30	10	20			
14	27.1	2	2	0	0	0	10	30	20	30	30	10	10	17	19	27
			1	15	10	5	5	20	30	30	40	20	20			
16	34.68	1	2	15	20	10	0	20	40	30	30	20	10	17	42	25
			1	0	5	0	5	30	30	20	30	40	20			
17	19.99	2	2	0	0	10	5	40	30	40	40	20	10	17	19	32
			1	5	5	5	5	30	50	30	50	10	10			
18	18.56	1	2	5	5	10	10	40	50	50	20	20	20	17	25	17
			1	0	0	0	0	40	40	40	30	20	20			
19	18.23	2	2	10	20	5	5	60	40	30	10	40	10	17	52	25
			1	10	15	20	10	30	50	50	50	10	10			
20	18.82	1	2	15	15	15	10	30	30	30	50	10	20	17	21	23

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			1	10	5	10	15	40	40	20	20	30	10			
21	17.82	2	2	5	0	0	0	40	30	40	20	30	10	17	16	25
			1	10	5	0	0	50	20	60	30	10	10			
22	31.16	2	2	5	0	0	0	50	50	40	50	40	10	17	20	24
			1	5	0	5	0	10	10	40	30	50	5			
23	26.09	2	2	5	5	0	0	20	50	30	20	20	20	17	18	16
			1	10	15	15	15	40	50	50	50	20	20			
24	31.76	1	2	5	5	15	15	30	40	40	40	0.999	40	17	16	17
			1	0	0	0	5	50	40	30	40	20	10			
27	37.93	1	2	5	5	5	15	30	20	30	40	40	20	17	12	14
			1	10	0	5	0	30	50	30	30	20	20			
28	34.53	1	2	10	5	5	5	40	50	30	20	40	10	17	19	26
			1	5	5	5	0	40	50	40	40	40	15			
29	34.3	1	2	5	0	10	10	20	40	40	30	20	10	17	25	25
			1					40	30	30	30	40	20			
30	22.89	1	2					40	20	20	20	30	20	17	25	39
			1	5	0	0	5	20	40	20	30	50	10			
33	17.44	2	2	0	0	0	5	30	40	30	30	60	20	17	15	29
			1	10	5	5	10	40	50	50	30	50	10			
35	21.52	1	2	5	0	0	5	40	40	40	40	60	20	17	14	20
			1	0	0	0	0	20	40	20	30	60	20			
36	23.89	1	2	0	5	0	0	40	30	30	30	60	10	17	19	22

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Data from the group with hearing loss

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Case	Age	Gender	Ear	Degree	Config.	BTR 0.5kH	BTR 1kHz	BTR 2kHz	BTR 4kHz	SSR 0.5kHz	SSR 1kHz	SSR 2kHz	SSR 4kHz	ABR-TB 0.5kHz	ABR-Click 2-4kHz	Testing time PT	Testing time SSR	Testing time ABR
			1	1	1	45	40	40	60	80	70	70	70	90	50			
E001	17.71	2	2	1	1	40	40	35	35	70	70	60	60	90	40	20	24	19
			1	2	2	30	45	45	50	40	100	70	60	60	80			
E002	17.24	2	2	2	2	40	65	60	55	80	70	80	70	0.999	80	20	28	18
			1	2	1	45	45	45	40	0.999	60	60	0.999	50	40			
E003	16.9	2	2	2	1	55	45	60	65	80	0.999	0.999	0.999	60	90	20	13	33
			1	4	1	80	65	75	65	85	85	0.999	80	95	85			
E004	16.73	2	2	4	4	85	85	75	65	90	0.999	95	80	100	90	20	25	24
			1	3	2	40	65	80	70	50	90	90	70	0.999	80			
E005	18.36	2	2	2	2	30	45	65	55	50	70	70	70	65	60	20	48	56
			1	4	4	95	90	85	70	95	0.999	0.999	90	0.999	90			
E006	18.8	1	2	4	1	80	75	80	80	0.999	95	0.999	95	0.999	85	20	16	19
			1	2	6	25	25	55	65	40	80	70	60	60	50			
E007	18.38	2	2	1	6	10	10	45	60	30	40	60	80	60	70	20	47	28
			1	2	6	50	40	60	70	50	50	50	50	60	85			
E008	17.57	1	2	2	3	45	40	40	55	80	50	60	95	80	60	20	33	25
			1	1	1	20	40	25	25	50	40	20	20	50	30			
E009	13.09	2	2	0	4	30	40	20	10	40	40	40	30	50	30	20	44	34
			1	1	4	50	45	30	20	50	70	80	60	70	30			
E010	17.71	2	2	4	4	105	105	75	70	80	80	90	0.999	0.999	80	20	43	30
			1	4	1	80	75	75	75	80	90	90	0.999	70	85			
E011	16.26	1	2	4	1	85	85	95	85	90	100	100	0.999	80	105	20	19	17
			1	4	2	50	75	110	110	70	100	0.999	0.999	0.999	65			
E012	15.17	1	2	4	2	55	80	115	105	80	0.999	0.999	0.999	0.999	95	20	21	24
			1	1	5	15	25	50	35	30	40	70	50	30	40			
E013	16.84	2	2	1	6	10	35	25	35	30	30	50	50	50	40	20	23	26
			1	3	3	25	35	80	85	30	60	90	100	60	95			
E014	16.68	2	2	2	3	30	30	80	70	40	60	90	90	50	70	20	38	31
			1	4	5	45	95	90	80	80	100	0.999	0.999	80	85			
E015	18.12	1	2	4	2	55	90	100	105	90	0.999	110	110	0.999	0.999	20	27	19
			1	3	2	35	55	70	70	45	65	65	85	40	90			
E016	14.51	2	2	3	2	35	50	70	70	45	95	95	95	70	70	20	21	19
			1	5	2	60	70	110	0.999	70	80	0.999	0.999	80	95			
E017	15.59	2	2	5	3	55	60	105	115	70	60	0.999	110	0.999	75	20	19	19

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			1	4	2	40	75	85	105	60	0.999	100	90	70	105		
E018	16.91	1	2	0	1	5	5	5	0	40	40	50	40	50	50	20	34	17
			1	4	5	80	85	70	105	90	100	80	0.999	0.999	75		
E019	16.49	2	2	5	1	115	115	0.999	0.999	0.999	0.999	0.999	0.999	0.999	105	20	17	25
			1	1	3	0	10	60	90	0.999	60	90	100	20	40			
E021	13.52	1	2	0	3	0	5	10	75	50	50	30	110	60	90	20	43	25
			1	4	1	85	90	80	70	100	90	110	90	90	65			
E022	12.82	2	2	5	5	95	70	105	0.999	80	0.999	0.999	0.999	100	95	20	33	21
			1	5	1	100	105	110	0.999	80	110	110	0.999	0.999	105			
E025	21.04	1	2	5	3	65	110	115	120	80	0.999	110	0.999	80	0.999	20	19	11
			1	5	1	110	110	110	110	0.999	110	105	0.999	120	0.999			
E026	19.03	2	2	5	1	105	105	95	0.999	0.999	110	100	105	0.999	105	20	10	14
			1	0	1	20	10	20	30	30	40	40	50	40	30			
E027	17.57	1	2	5	1	95	95	95	110	100	110	90	110	0.999	85	20	37	25
			1	5	1	105	105	105	0.999	100	100	0.999	0.999	0.999	85			
E028	18.69	1	2	5	4	110	110	95	100	110	0.999	110	0.999	0.999	0.999	20	12	9

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Effect of gender

Behavioural threshold at:	0.5 kHz p-level:	.2377	Insignificant
	1.0 KHz	.0054	Significant
	2.0 KHz	.0188	Significant
	4.0 KHz	.0000	Significant
Mf ASSEP MRLs at:	0.5 kHz	.0364	Insignificant p<.01
	1.0 kHz	.3702	Insignificant
	2.0 kHz	.1107	Insignificant
	4.0 kHz	.0261	Insignificant
ABR Click MRL:		.7130	Insignificant
ABT Tone burst MRL at:	0.5 kHz	.0193	Insignificant

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Appendix B: ABR data analysis for threshold estimates

INDIVIDUAL FORM

Code: N / E	
Ear: 1(left) or 2 (right)	
Minimum levels	
ABR click:	
ABR tone burst:	
Confidence rating:	

INTERRATER FORM

Code: N / E				
Ear: 1(left) or 2 (right)				
Minimum levels	Rater 1	Rater 2	Rater 3	Average
ABR click:				
ABR tone burst:				
Confidence rating:				

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Appendix C: Informed consent letter

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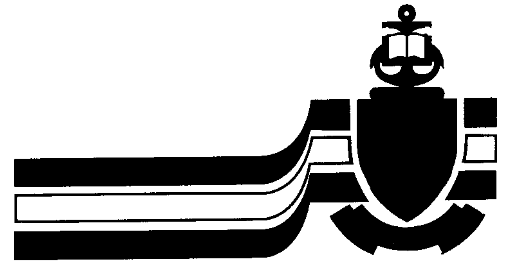

University of Pretoria

Pretoria 0002 Republic of South Africa Tel (012) 420-2357 / 420-2816 Fax (012) 420-3517 http://www.up.ac.za

Department of Communication Pathology
Speech, Voice and Hearing Clinic

January 2001

Dear Sir / Madam

Thank you for showing interest in this research project being conducted at the Hearing Clinic, Department Communication Pathology at the University of Pretoria. The Audiology Department is very excited about the arrival of the Audix Steady State Response Evoked Potential equipment, a state-of–the art objective hearing evaluation procedure. We are currently undertaking the clinical trials of the equipment and we need your assistance. We need to establish norms on normally hearing as well as hearing impaired ears and we kindly ask you to participate in our study.

Procedure
You will undergo a standard hearing test with air and bone conduction. In the case of you making use of amplification, we will only determine unaided thresholds.

An Auditory Brainstem Response test will then be conducted. No response is required during this testing procedure. You will simply be asked to lie down on a bed with three electrodes attached to your head and insert earphone in you ears.

The last test will be conducted with the Audix equipment. No response is required during this test procedure. You will simply be asked to lie down on a bed with three electrodes attached to your head and insert earphones in your ears.

All three procedures are non-invasive and only one procedure requires subjective responses. The entire test battery should take approximately one and a half hours to complete. All acquired information will be stored on a database and treated as confidential and no names will be used. At your request, a copy of your results will be made available to you.
Thank you for your assistance.

Should you require any additional information, you are welcome to contact us.

Yours sincerely

Prof. René Hugo	Me Dunay Schmulian	Mr De Wet Swanepoel
Research Supervisor	Researcher	Researcher

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REPLY SLIP

University of Pretoria
Department Communication Pathology

Surname:____________________ Name:__________________________

Date of Birth:______________________

Age:____________________________

First language:___________________

Occupation:______________________

Contact numbers:____________________ ___________________________

Please complete the following where applicable

How long have you had a hearing problem?

____

Do you know the cause of the hearing problem?

____

Do you wear hearing aids?

____

If so, how long have you been making use of hearing aids?

____

Do you work in a noise environment?

____

If so, do you wear hearing protection?

____

I, ____ (state full name) hereby consent to participate as a research subject in the clinical trials of the Audix Steady State Evoked Potential equipment at the Hearing Clinic, Department of Communication Pathology at the University of Pretoria. I understand that the information will be used for research purposes only and is confidential.

_________________________ ___________________________

Signature Date

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