FREQUENCY SPECIFICITY OF NARROW BAND CHIRP ABR AND IT's CORRELATION WITH BEHAVIORAL THRESHOLDS

Kanchan Kumari

Register No: 12AUD013

A Dissertation Submitted in part fulfillment of final year

Master of Science [Audiology]

University of Mysore

ALL INDIA INSTITUTE OF SPEECH AND HEARING,

MANASAGANGOTHRI, MYSORE - 570 006

MAY, 2014

Dedicated to my guide & my parents

CERTIFICATE

This is to certify that this dissertation entitled **"FREQUENCY SPECIFICITY OF NARROW BAND CHIRP ABR AND IT's CORRELATION WITH BEHAVIORAL THRESHOLDS"** is a bonafide work submitted in part fulfillment for the degree of Master of Science (Audiology) of the student (**Registration No. 12AUD013)**. This has been carried out the under guidance of a faculty of this institute and has not been submitted earlier to any other university for the award of any Diploma or Degree.

Mysore

May, 2014

Dr. S. R. Savithri
Director
All India Institute of Speech and Hearing
Manasagangothri, Mysore - 570 006.

CERTIFICATE

This is to certify that dissertation entitled **"FREQUENCY SPECIFICITY OF NARROW BAND CHIRP ABR AND IT's CORRELATION WITH BEHAVIORAL THRESHOLDS"** has been prepared under my supervision and guidance. It is also certified that this dissertation has not been submitted earlier to any other university for the award of any diploma or degree.

Mysore
May, 2014

Mr. Sreeraj K.
Guide
Lecturer in Audiology
All India Institute of Speech and Hearing
Manasagangothri, Mysore – 570 006.

DECLARATION

This is to certify that this master's dissertation entitled **"FREQUENCY SPECIFICITY OF NARROW BAND CHIRP ABR AND IT's CORRELATION WITH BEHAVIORAL THRESHOLDS"** is the result of my own study under the guidance of a faculty at All India Institute of Speech and Hearing, Mysore, and has not been submitted earlier to any other university for the award of any Diploma or Degree.

Mysore **Register No: 12AUD013**

May, 2014

ACKNOWLEDGEMENTS

I would like to thank god for giving me the strength to purse this research and for giving me support from the right people at the appropriate time to complete this dissertation.

Sreeraj sir…..All the efforts wouldn't have resulted in success without your guidance. Inspite of your busy schedule, you always found time to listen the problem and patiently came to the solution in the easiest way. Thank you so much sir….for being so approachable & bearing me with my never ending doubts ☺ ☺ …and my laptop for never ending technical problems ;-) This dissertation would n't ve completed on time, without ur time, patience & support….thank u so much sir for being so calm and cool throughout …☺☺☺

Thanku mumma : ☺ ☺ for believing in me and giving me the strength to stay back for long 6 years in aiish. !! papa, you have given me the greatest gift anyone can give another person. Thanku for helping me make the decision of choosing this field.

I thank the director, Dr.S.R Savithri for granting me permission to carry out this dissertation.

My sincere thanks to Dr. Ajit kumar, HOD audiology for permitting me to use the instrument in the department and granting permission even on weekends.

Ganpati sir, jitin sir & kishor sir…..thanku so much for agreeing to open the department on all weekends…:-)

Sandeep sir & Nike sir….thank u so, much for agreeing to shift the instrument in EP-lab .

Jobish sir….thank you for helping me right from beginning….to selecting the topic…for deciding the method & interpreting the results.

I take this opportunity to express a deep sence of gratitude to Jijo sir…for his cordinal support, valuable information & thank you so much sir for making the statistical analysis in the easier way.

Thank u laxme mam, for helping me directly & indirectly….:-)

Vinu….i don't know from where to begin…you are one of the bestest person in the world I have ever met…who stood by me through the ups and lows of my life…..treated me like a little girl and fulfilled all my silly demands…journey at aiish wouldn't have been possible without your care and support…..thank you so much for being always there…☺☺ love u lot….☺

Juhi…you have been more than just my twin, and the experience we have shared have just been extraordinary….thank you so much for being there throughout the journey to share all my silly secretes & frustrations...;-) gonna miss u a lot…!!

Astha & teju….am so glad to have friends like you..!! You have always helped me get over and laugh at all my bad experiences….gonna miss all the chit-chat that we shared….

Rojina & jyoti….thank you for the last movement help…it really meant a lot…☺☺

To d sweetest bro's….Sandeep & pradeep… Thank you for taking me out of stress with your silly jokes…love u always…☺

Thanks to all my classmates who have helped me survive this tough and hectic journey of aiish.

Lastly, I would like to thank all the participants of my study to have spared their valuable time.

TABLE OF CONTENTS

Chapter No.	*Title*	*Page No.*
1	Introduction	01
2	Review of literature	07
3	Method	23
4	Results and Discussion	31
6	Summary and Conclusion	46
	References	49

LIST OF TABLES

Table No.	*Title*	*Page No.*
Table 3.1	Pure tone threshold at four audiometric frequencies for HI individuals	25
Table 3.2	Stimulus and acquisition parameters for NB-chirp ABR	29
Table 4.1	Mean and standard deviation for pure tone thresholds and NB-chirp ABR thresholds at 500,1000,2000Hz & 4000Hz for individuals with normal hearing	33
Table 4.2	Predicted NB-chirp ABR thresholds in individuals with normal hearing	33
Table 4.3	Predicted NB-chirp ABR thresholds in individuals with mild hearing loss	35
Table 4.4	Predicted NB-chirp ABR thresholds in individuals with moderate hearing loss	35
Table 4.5	Correlation across different frequencies in individuals with normal hearing	37
Table 4.6	Correlation across different frequencies in individuals with mild hearing loss	38
Table 4.7	Correlation across different frequencies in individuals with moderate hearing loss	39
Table 4.8	Correlation between NB-chirp ABR thresholds and behavioral at different frequencies across three groups	40
Table 5.1	Correction factor (dBHL) between pure tone and NB chirp ABR thresholds in individuals with normal hearing sensitivity	47

LIST OF FIGURES

Figure No.	***Title***	***Page No.***
Figure 2.1	Spectral representation of click, exact chirp and flat spectrum chirp	17
Figure 2.2	NB-chirp envelop in relation to the broadband CE-chirps	21
Figure 3.1	The timing of the different stimuli relative to the start of normal data acquisition	25
Figure 4.1	Latency-intensity functioning across different frequencies for individuals with normal hearing	41
Figure 4.2	Latency-intensity functioning across different frequencies for individuals with mild hearing loss	43
Figure 4.3	Latency-intensity function across different frequencies for individuals with moderate hearing loss	44

Chapter 1

Introduction

A person who is not able to hear as well as someone with normal hearing thresholds of 25 dB or better in both ears is said to have hearing loss (World health Organization, 2013). A detailed audiological evaluation is the first step if we suspect a hearing problem and is essential before commencing rehabilitation. Comprehensive audiological evaluation includes many subjective and objective evaluations which include otoscopy, pure tone audiometry to estimate hearing thresholds, speech audiometry to obtain thresholds for speech awareness and recognition, immittance evaluation to determine middle ear status, otoacoustic emissions to check functioning of outer hair cells and auditory evoked potentials (AEPs) (National Centre For Hearing Assessment and Management; Audiologic Guidelines for the Assessment of Hearing, 2012). Auditory evoked potentials represent neural responses of the auditory pathway, from the eighth nerve to the cortex, to externally presented stimuli. They are usually grouped in to various categories based on the latency and this grouping corresponds roughly to the site of generation.

In clinical practice, auditory brainstem response (ABR) is the widely used AEP for threshold estimation and neurodiagnosis (Hall, 1992). ABR can be recorded using broadband signals like clicks (Stapells & Oates, 1997; Gorga et al., 2006) broadband chirps (Dau, Wegner, Mellert, & Kollmeier, 2000), modulated speech signals (Kathy & Carolyn, 2005), as well as frequency specific stimuli like tone burst (Gorga, Kaminski, & Beauchaine, 1988; Hall, 1992), tone pip, click with notch noise (Picton, Ouellette, Hamel, & Smith, 1979; Stapells, Gravel, & Martin, 1995) and click with white noise (derived band technique) (Don, Ponton, Eggermont, & Masuda, 1994). Each of them has their own advantages as well as limitations.

Clicks are the most widespread stimulus used to estimate ABR thresholds. Even though the click is characterized by rapid onset, its broad spectral content may not make it the best choice for frequency specific ABR testing (Stapells, Picton, & Durieux-Smith, 1994; Gorga et al., 2006). When obtaining an ABR using tone bursts, the brief stimulus onset may cause excessive spectral splatter producing response contributions from unwanted regions of the cochlea; thus, reducing the frequency specificity of the ABR. The presence of a sloping sensory neural hearing impairment creates additional difficulties for achieving frequency specificity because of the likelihood that lower frequency cochlear regions, with less sensory damage, would contribute to the evoked response (Picton et al., 1979; Stapells & Picton, 1981; Stapells et al., 1994; Stapells et al., 1995; Stapells & Oates, 1997). Hence, it was necessary to use some form of masking noise to restrict the regions of the basilar membrane contributing to the ABR. Notched noise masking used in conjunction with the tone burst ABR, limits the evoked response to those frequencies within the notch, thereby reducing the likelihood of spectral splatter and increasing frequency specificity. However, the fact of occurrence of extra peaks in the waveform and poor wave morphology due to spread of low frequency masking noise into the notch, limits its usage in obtaining frequency specific responses (Hall, 1992).

Temporal dispersion taking place in the cochlea due to the usage of above mentioned stimuli decreases the ABR peak amplitude, which further smears the responses in time. Thus, in order to produce clearer and more easily detectable responses while retaining the frequency specificity; some form of compensation for the latency was applied, namely, travelling wave delay compensation. The travelling wave delay compensation can be done in two ways, input compensation and output compensation (Elberling, Don, Cebulla, & Sturzebecher, 2007). Output compensation can be obtained by time-shifting the narrow band activity which could be obtained by using stacked ABR (Don, Masuda, Nelson, & Brackmann, 1997; Don, Kwong, Tanaka, Brackmann, & Nelson, 2005). In input compensation latency characteristics are taken into account to design the input signal. It refers to the way to compensate for the traveling time by shifting the different frequency components of the stimulus. This is done by allowing the low-frequencies to appear before the high-frequencies. Such a click with re-shuffled frequency components is called a Chirp.

So, the researchers generated different stimuli (based on formulas and cochlear model) to compensate for the travelling wave delay in order to get synchronous responses through ABR and one of such stimuli is chirp. It is a family of stimuli, which comprises of broadband chirps (M-chirp, A-chirp, Exact chirp stimuli and O-chirp) and narrow band chirps. Chirp has been named in honor of Claus Elberling. Predominantly Claus Elberling (CE)-Chirp can be classified in 2 types: (1) broadband chirps and (2) narrow band chirps. The Broadband CE-Chirp was designed using a delay model based on derived band ABR latencies, where higher frequencies were delayed with respect to lower frequencies (called as rising chirps) or vice versa (called as falling chirps) (Dau et al., 2000; Elberling et al., 2007).

Dau et al. (2000) recorded ABR in 10 normal hearing individuals and it was found that ABR elicited by rising chirp produced larger wave V amplitude and good wave morphology than the corresponding click stimuli. Rising chirp would enable the inclusion of activity from low frequency region; where as in click, neural synchrony decreases with decreasing travelling wave velocity in the apical region. Bell, Allen and Lutman (2002) opined that broad band chirps may have the disadvantage of a wider spectral spread than tone bursts and therefore elicit responses from unwanted frequency regions of the basilar membrane which further compromises the frequency specificity. Studies on adults have suggested that the amplitude of the broadband CE-Chirp response can be up to twice the size of the conventional click response amplitude (Elberling et al., 2007; Elberling & Don, 2010; Elberling, 2011).

Thus, from the above mentioned studies it can be concluded that broadband chirps would give an approximate estimation of behavioral thresholds but not accurate and it doesn't enable us to get frequency specific information. So, in order to overcome with these limitations and to retain frequency specific thresholds alternate stimuli need to be used.

Need of the study

When estimating hearing thresholds using the ABR, it is important that responses are frequency specific and are as close to the behavioral pure-tone hearing thresholds as possible. As discussed in the introduction, different types of stimuli are used for eliciting ABR. Each of them has its own advantages and limitations. So, it is important to select stimuli which can provide frequency specific information regarding hearing thresholds, at the same time can prevent the temporally smeared responses. Recently, narrowband chirps (NB Chirps) have been introduced in electrophysiological assessment (Elberling, 2011). These are octave-band limited chirp stimuli centered at 0.5, 1, 2 and 4 kHz.

Rodrigue, Ramos and Lewis (2013) compared ABRs elicited by tone burst and narrow band CE-chirp in 40 infants with normal hearing, whose age ranged from 1 to 3 months (average 2.6 months). ABRs were elicited at four frequencies including 500, 1000, 2000 and 4000 Hz at four stimulus levels: 80, 60, 40 and 20 dB nHL for tone burst as well as for narrowband CE-chirp. Latency and amplitude characteristics were analyzed for both stimuli. Results revealed that NB-chirps generated shorter latencies and higher amplitude than tone burst. Latencies were shorter for NB chirp especially at lower frequencies. Thus it was concluded that due to large amplitude, NB chirp can facilitate easy visual detection of waveforms than tone bursts especially at lower levels which further reduces the testing time especially in infants. Earlier studies mentioned in the literature in this regard have been done mainly in infants (Ferm, Lightfoot, & Stevens, 2013). So, there is a need to apply the investigations using NB-Chirp in adults as well.

Dau et al., (2000) recorded chirp evoked ABR in 10 normal hearing individuals and reported that the ABR elicited by chirp stimulus involves cochlear processing and evokes large wave V response at low sensation levels with good wave morphology. It will be interesting to see the effect of cochlear processing in individuals with cochlear hearing loss.

Studies done so far mainly focused on correlating NB-chirp-evoked ABR thresholds with behavioral thresholds in normal cochlear processing. There is a need to correlate the same in individuals with cochlear pathology to verify the frequency specificity of NB-chirps Also, the clinical utility of NB-chirp ABR as an objective indicator for threshold estimation has to be probed into.

Aim of the study

To compare narrow band chirp evoked ABR thresholds with behavioral thresholds in individuals with normal hearing sensitivity and those with cochlear hearing loss and to establish normative for NB-chirp ABR in adults.

Objectives of the study

1. To find the correction factor for converting ABR nHL (normal hearing level) thresholds which were obtained using NB-chirps to eHL (estimated true hearing level) threshold in order to establish normative for NB-chirp evoked ABR.
2. To find the correlation between behavioral thresholds and NB CE-chirp evoked ABR thresholds obtained using frequency specific chirps for individuals with normal hearing sensitivity and those with cochlear hearing loss and to validate the clinical utility of this stimulus.
3. To determine latency-intensity function for NB-chirp evoked ABR wave V in individuals with normal hearing and in those with cochlear hearing loss.

Chapter 2

Review of literature

The auditory evoked potentials (AEPs) are the electrical responses of the auditory nervous system to auditory stimuli (Stapells, Picton, Abalo, Read, & Smith, 1985; Gelfand, 2007). AEPs that are recorded from the scalp represent the contribution of neural events that arise from many discrete and neural generating sites along the auditory pathway. Thus, AEPs can be used to test the integrity of nervous system (Gelfand, 2007). These potentials can be described in various dimensions such as time of occurrence (early, middle and late latency responses), speed of occurrence (fast and slow), based on anatomy (electrocochleography and auditory brainstem responses) and based on the property of response generation (exogenous and endogenous); or some more specific generator properties (stimulus related and event related) as described by Goldstein and Frye-osier (1984).

Short latency AEPs like ABR is used clinically for threshold estimation and neurodiagnosis (Hood, 1998). Different kinds of stimuli are used to evoke brainstem responses. They can be generally classified in to clicks (Stapells & Oates, 1997; Gorga et al., 2006), tone burst (Hall, 1992), tone burst with notched noise (Picton et al., 1979; Stapells et al., 1995), chirps (Dau et al., 2000) and click with white noise (derived band technique) (Don et al., 1994). Due to broad spectral content and rapid onset, clicks are believed to elicit synchronous discharge from large proportion of nerve fibers in relatively brief amount of time (Kodera, Yamane, Yamada, & Suzuki, 1977; Gorga & Thornton, 1989; Gorga, et al., 2006). The click evoked ABR waveform generally consists of seven peaks, all occurring within the first 10 ms after the signal onset. Of the seven peaks, wave I, III and V are significantly robust for clinical use. The most robust peak can be elicited near threshold level is wave V (Stapells, et al., 1985).

Don and Eggermont (1978) recorded click ABR at 60 dBSL in noise high passed at various cutoff frequencies separated by ½ octave steps in normal hearing adults subjects. By applying a derived responses technique, narrow-band contributions to the ABR from specific portions of the basilar membrane were revealed. Latencies and amplitude of various waves in the derived ABR were recorded. Results indicated that nearly the whole cochlear partition can contribute to the brainstem responses. But, when they looked the contribution to the ABR of various regions along the cochlear partition, using derived band method they found that for high-frequencies, a normal response pattern is generated by those high - frequency regions along the cochlear partition. As the central frequency (CF) became lower, these appears to be in derived response less contribution to the earlier peaks, but good contribution to wave V. From the results they made an observation that above 2 kHz, the wave V behavior was the same as for the earlier waves; below 2 kHz, however, wave V amplitude remains nearly constant for whole range of CF'S while waves I & III show a rapid drop in amplitude with decreasing CF. It could be inferred from the above study that click ABR contribution is more above 2 kHz than at lower frequencies.

Gorga, Worthington, Reiland, Beauchaine and Goldgar (1985) compared ABR and pure-tone behavioral thresholds in individuals with cochlear hearing loss. They found that click-evoked ABR thresholds appeared to be related most closely to audiometric thresholds at 2000 and 4000 Hz; with relatively poor agreement at either 1000 or 8000 Hz. Poor agreement at higher frequencies was observed due to broad-band spectrum of clicks. Also, in cochlea the response of a click is not entirely synchronous; that is, the peak of the response occurs several milliseconds later in the low frequency channels than it does in high frequency channels (Bekesy & Wever, 1960). As a consequence, ABR responses are largely generated by synchronized activity of high frequency region when clicks are used (Dau et al., 2000). Thus, it does not provide frequency specific information

To overcome the limitation of clicks, an alternative approach is to use a stimulus that has sufficiently rapid onsets so that they can effectively elicit an ABR (which is an onset response requiring neural synchrony); while at the same time maintaining a relatively well-defined stimulus in the frequency domain. To serve this purpose, a short duration tone burst stimuli can be utilized. The tone burst has primary energy at a single characteristic frequency and ideally contains no energy at other frequencies (Hall, 1992). It is believed to provide more frequency specificity and allows for reasonably accurate estimation of the pure-tone audiogram (Gorga et al., 1988; Gorga et al., 2006). However, the tone burst has a brief stimulus onset which may cause excessive spectral splatter producing response contributions from unwanted regions of the cochlea. The splatter occurs when using high intensity stimuli (80 dBSPL and higher) and/or low frequency stimuli which spreads into the higher frequency regions of the cochlea thus, reducing the frequency specificity of the ABR which results in poor wave morphology and poor replicability. Spectral splatter is a particular problem when assessing patients with steeply sloping hearing loss because contributions may arise from the frequency regions where the hearing is better (Picton et al., 1979; Stapells et al., 1985; Purdy & Abbas, 1989; Stapells et al., 1994). In these cases, it is necessary to introduce some form of masking that will restrict inappropriate areas of the basilar membrane from responding.

There are several different masking noises that can be used when assessing the ABR; including notched noise (Stapell, Picton, Durieux-Smith, Edwards & Moran., 1990; Hall, 1992), white noise (Stapells et al., 1994), high-pass noise (Don et al., 2005) and derived band masking (Don et al., 1994). Notched noise masking used in conjunction with the tone burst ABR, limits the evoked response to those frequencies within the notch, thereby reducing the likelihood of spectral splatter and increasing frequency specificity. Notched noise is defined as a broadband of noise that has been band rejected ("notched"); a specific range of frequencies has been removed from the noise (Hall, 1992). When obtaining a tone burst ABR with notched noise masking, both the stimulus and the masking noise are introduced at the same time and only the frequencies within the notch are involved in generating the ABR (Hall, 1992). Thus, using notched noise masking improves the frequency specificity of the tone burst ABR (Stapells & Oates et al., 1997). It does not require more acquisition time to record the notched noise tone burst ABR than it does to record the standard tone burst ABR because both the masker and the stimulus are presented simultaneously (Hall, 1992).

However, there are disadvantages to this method (Hall, 1992).

- ✓ The low frequency masking noise spreads into the notch.
- ✓ The morphology of the waveform is compromised when using notched noise masking. Wave V has a more broad shape and smaller amplitude and may sometimes be unidentifiable. When using tones presented at low to moderate intensity levels, the early waves (I, II, III and IV) are not typically present from 500 to 4000 Hz. These early waves may appear at higher intensity levels but only around 500-1000 Hz (Stapells & Oates, 1997).

- ✓ Extra peaks may appear in the waveform and be misinterpreted as wave V. It is important to remember that responses to tones usually occur at later latencies, which could lead to misinterpretation of earlier peaks as wave V.
- ✓ Using notched noise- masking overestimates the auditory threshold levels. (Orsini, Hurley, Jennifer, & Harvey, 2004)

Another masking noise technique that has been suggested to improve the frequency specificity of ABR to tones is white noise masking. The advantage of this type of noise is that it requires less complex instrumentation and calibration than high pass noise/notched noise and provides same frequency specificity as notched noise (Stapells & Oates, 1997). The disadvantage of white noise is that it results in response amplitude which is 33% lower than recorded in notched noise. This is due to partial masking of energy at the tone's nominal frequency (Stapells et al., 1994).

Stacked ABR is another tool to compensate for stimulus traveling delay in the cochlea and gives robust amplitude with less variance. Primarily two methods have been used to record stacked ABR. They are derived band technique and tone burst method. Don et al., (1994) were the first to record stacked ABR. They obtained frequency specific ABR using derived band technique and summed these responses by temporally aligning wave V in each derived band response. They used stacked ABR to investigate whether variability in cochlear response times would also lead to variability in click evoked ABR amplitude. They compared stacked ABR recording with unmasked ABR recording in 43 individuals with normal hearing and concluded that variability in amplitude is due to temporal difference in cochlear activation and response time is not related to the central conduction time. They also concluded that stacked ABR reduces the residual noise and hence reduces the variability of amplitude of ABR peak between runs. The amplitude of stacked ABR wave V reflects more directly the total amount of cochlear activity. The ABR amplitude for the wave V increases with derived band temporally aligned responses (stacked ABR) as compared to summed natural derived band responses in an individual with normal hearing (Don et al, 1994). The derived band method requires a masking technique that may not be readily available to the clinicians. Furthermore, relatively high level of noise is required for masking which may be annoying to the subject.

Philibert et al., 2003 developed stacked tone burst evoked ABR to overcome with the disadvantages of derived band stacked ABR. But, no significant difference between ABRs obtained using the tone burst method and derived band method was observed. The morphologies differed between two methods and relatively high reproducibility was noted with tone burst evoked ABR particularly at lower frequencies. This may be due to more basal ward spread of excitation and potentially giving a more synchronous response to low frequency tone burst than derived band ABR. The disadvantage is that it is inappropriate for middle and high frequency tones, which can lead to underestimation of hearing loss.

So, to overcome with the disadvantages of above mentioned stimuli and in order to get frequency specific responses other types of stimuli were generated to optimize the basilar membrane dispersion and to increase neural synchrony.

Chirp stimuli.

Chirp is another type of stimulus that is used to evoke ABR. The chirp is a transient sound, where the higher frequencies are delayed with respect to the lower frequencies, in order to produce simultaneous displacement maxima by canceling traveling-time differences along the cochlear partition (Dau et al., 2000). When an abrupt stimulus like clicks is used, discharging of the apical nerve fibers are temporally out of step with the least contribution from the basal and middle frequency nerve fibers. But, a chirp is designed specifically to temporally align all the neural elements of the auditory nerve by compensating the travelling wave delays (Elberling et al., 2007). The travelling wave delay compensation can be done in two ways, input compensation and output compensation. Output compensation can be obtained by time-shifting the narrow band activity which could be obtained by using stacked ABR. Input compensation refers to the way to compensate for the traveling time is to time shift the different frequency components of the stimulus. This is done by allowing the low-frequencies to appear before the high-frequencies. Such a click with re-shuffled frequency components is called a chirp.

In order to find the performance under two designed compensation techniques, Elberling and Don (2008) compared chirp amplitude ratio (amplitude of chirp/ amplitude of click) with the stacked amplitude ratio. Results demonstrated that stacked ABR has larger amplitude than the chirp ABR. Further, they also demonstrated that amplitude ratio was higher for stacked ABR than chirp ABR. However, more variations in the data were noticed for stacked ABR amplitude ratios than chirp ABR amplitude ratio.

Cebulla, Lurzand and Shehata-Dieler (2014) evaluated the waveform, latency and amplitude values evoked by chirp ABR in newborns and compared them with those evoked by click ABR in order to determine whether chirp-evoked responses are easier to detect at near-threshold values, and to assess the usefulness of the chirp stimulus in improving ABR detection thresholds in this population. Results revealed larger wave amplitude for chirp ABR compared to those evoked by clicks and the gain of the amplitude was more at lower stimulation levels along with the shorter latencies for chirp stimuli than click. Thus it was concluded that chirp would be the best stimulus in order to estimate approximate threshold values, especially in infants.

Suresh (2013) investigated whether amplitude of standard chirp evoked ABR was same as tone evoked stacked ABR in individuals with normal hearing and in those with cochlear pathology. They recorded standard chirp evoked ABRs (input compensation) as well as tone burst evoked stacked ABR (output compensation) in both the groups. Standard chirp consisted frequency range of 1000 Hz to 10 kHz. Results showed a significant difference in wave V amplitude between stacked tone ABR and chirp evoked ABR. This was probably because amplitude of chirp evoked ABR is assumed to be the sum of responses of all the neurons of VIIIth cranial nerve; whereas stacked ABR amplitude is derived by adding neural responses for different frequencies obtained individually and thus, multiple compound potentials of different groups of neurons to different frequencies will be added up. Hence, summation of multiple compound potentials would always give a higher value than single compound potentials resulting in increased amplitude for stacked ABR. Based on the results obtained by Elberling and Don (2008, 2010) and Suresh (2013), it can be concluded that chirp ABR may be a good tool in order to get an approximation of behavioral thresholds.

The ‘Claus Elberling Chirp’ (CE-Chirp) is a family of stimuli designed to compensate for this cochlear travel delay and provide enhanced neural synchronicity (Shore & Nuttall, 1985; Lutkenhoner, Kaufmann, Pantev, & Ross, 1990; Dau et al., 2000). The stimuli family includes a broadband CE-Chirp as well as narrow band CE-Chirp stimuli for frequency specific testing.

The broadband chirp.

The broadband chirp (Elberling, et al., 2007) is an example of a chirp stimulus developed to compensate for timing delays associated with the cochlear travelling wave. Stimulation generated by broadband sounds occurs for different frequency areas at different times, resulting in a slight temporal smearing of the ABR response because sound takes a finite time to traverse the basilar membrane. The outcome is a smaller, more poorly defined response (Elberling et al., 2010). The chirp attempts to optimally overcome the temporal smearing issues by compensating for the cochlear travelling wave delay. Studies on adults have suggested that the amplitude of the broadband chirp response can be up to twice the size of the conventional click response amplitude (Elberling, et al., 2007; Elberling et al., 2010). Broadband chirps further can be classified in rising and falling chirps.

1. Rising chirp stimuli starts with low frequency and sweeps nonlinearly in time towards high frequencies. The rising chirps are further classified in to A-chirps, O-chirps and M-chirps. (Dau et al., 2000).
2. Falling chirp stimuli starts with high frequency and sweeps nonlinearly in time towards low frequencies.

Comparison of rising and falling chirp stimuli.

Dau, et al. (2000) compared wave V amplitude of ABR using rising and falling chirp stimuli. Results of the study indicated that for all stimulation levels of 10 - 40 dBSL, wave V amplitude was significantly larger for rising chirps than for falling chirps. For levels of 20 - 40 dBSL the amplitude of reversed chirps was also significantly lesser than click responses whereas the difference was not significant for 10 dBSL. This was due to the fact that using reversed chirp will decrease the neural synchrony instead of increasing it. Falling sweeps produce sequential activation of high- frequency fibers followed by low-frequency fibers (Dau et al., 2000). This may lead to a desynchronized neural activation at the brainstem level, as implied by the results of Shore and Nuttall (1985) at the level of VIIIth nerve and CN. Thus, rising chirp stimuli were used in all the studies to evoke synchronized neural responses.

Different studies on rising chirp had utilized different models and formulas to generate the rising chirp stimuli. Different types of rising chirps used in these studies were:

1) *A-chirp:* A- chirp is ABR based chirp stimuli which was developed based on the tone-burst evoked ABR data by Gorga et al. (1998). They used tone bursts at ten frequencies (0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 6 and 8 kHz) and nine intensities (20 to 100 dBSPL in 10 dB steps) and obtained this stimulus.
2) *O-chirp:* also called as otoacoustic emission (OAE) based chirp stimulus, was developed based on the experimental stimulus frequency otoacoustic emissions (SFOAEs) data by Shera and Guinan (2000). They did experiments for stimulus frequencies in the range from 0.5 to 10 kHz in humans, at the level of 40dB SPL and from this data they formulated the chirp stimulus.
3) *Exact chirp stimuli:* this stimulus was generated by Dau, et al. (2000) using De boer's cochlear model (1980). In this stimulus spectral weightage to higher frequencies was not given; thus the spectrum of the chirp stimuli was not flat.
4) *M-chirp:* also called as modified chirp; this was used in the study by Dau et al (2000). They developed chirp with a flat magnitude spectrum and denoted it as the "flat-spectrum chirp". The time course of the chirp developed and used in the study by Dau, et al., (2000) was determined by the travelling-wave velocity along the partition as derived by de Boer (1980), and the functional

relationship between stimulus frequency and place of maximum displacement (Greenwood, 1990).

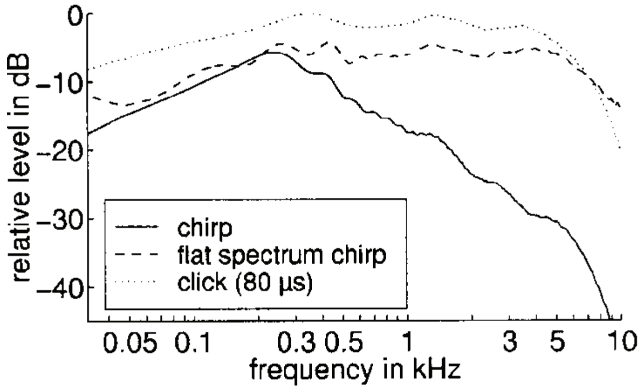

Figure 2.1 spectral representations of click, exact chirp and flat spectrum chirp developed by Dau et al (2000). Adapted from Dau, Wegner, Mellert and Kollmeier, (2000).

Out of all these chirp reported in literature most commonly used chirp was M-chirp (Dau et al., 2002; Feobel & Dau, 2004; Agung, Purdy, Patuzzi, Beirne, & Newall, 2005).

Frequency specificity of M-chirps:

Wegner & Dau (2002) examined the usefulness of the chirp for retrieving frequency specific information. The version of the chirp having a flat magnitude spectrum was used (M-chirp). The flat spectrum chirp and a click were used in ABR experiments involving high-pass masking noise, with cut off frequencies of 0.5, 1, 2 & 8 kHz and notched-noise masking paradigms in 9 normal-hearing young adults. Results indicated that chirp generated higher wave-V amplitudes than the click in all high-pass masking conditions. However, neither the amplitudes of the narrow-band responses nor of the notched-noise responses differed significantly between the chirp and the click. The authors concluded that the applied one-octave bandwidths were not wide enough to demonstrate the higher neural synchronization with the chirp stimulus. Finally, a low frequency chirp was compared to a 250 Hz tone pulse with comparable duration and amplitude spectrum and it was found that at low and medium levels of stimulation the low-frequency chirp produced larger wave-V amplitudes than the tone pulse

In another study by Fobel and Dau (2004), ABRs were elicited using three different chirp stimuli- M-chirp, A-chirp and O-chirp. The resulting ABRs were compared with each other and with the response from the traditional click stimulus. The result was that the A-chirp performed better than the O- and M-chirps, especially at low stimulus levels, whereas there were no great differences between the O- and M- chirps at low and medium stimulus levels. Nevertheless, all chirps performed better than the click stimulus when comparing the wave V amplitudes.

The results of both studies suggested that the characteristics of the optimal stimulus vary with the level of the stimulus. In the study by Dau et al. (2000), the chirp did produce larger wave V amplitude than the click also for the levels 50- 60 dB SL, but the difference was not significant any more. The authors suspected that the decrease in performance at high levels was caused by cochlear upward spread. The A-chirp by Fobel and Dau (2004) was fitted to measurement data from multiple frequencies and levels. As the level was increased, the temporal structure of A-chirp changed. More specifically, the louder the stimulus, the shorter the chirp. Elberling et al., (2010) noted that the duration of the best performing chirp decreases as the level of stimulation increases. This observation was made when they conducted experiment with five chirps of different durations at three levels of stimulation. Their results showed that shorter chirps produced the largest wave V amplitudes for higher stimulus levels.

Suresh (2013) investigated latency and amplitude differences between ABR elicited by standard chirp and modified chirp. The study aimed to find the latency and amplitude differences evoked by standard chirp (0.1Hz to 10 kHz) evoked ABR and modified chirp (generated using MATLAB software constituting the frequency range of 250 - 8000Hz) evoked ABR in normal and hearing impaired individuals. Results revealed that, standard chirp ABR amplitude was higher than modified chirp in both the groups. This was observed because large frequency range resulted in activation of more number of nerve fibers which gave rise to higher amplitude for standard chirp's compared to modified chirps where less number of neural fibers wee activated due to restricted frequency range. For both the groups, Latency obtained by standard chirp was longer compared to modified chirp, which could be due to more involvement of low frequency component in standard chirp than modified chirp. Lower frequency component excited apical region of the cochlea thus increasing the travelling time which further resulted in increased latency for standard chirp compared to modified chirp.

Disadvantages of using broad band chirp.

- ✓ Broad band chirp stimuli can't provide frequency specific information (Dau et al., 2000)
- ✓ **Across channel attraction:** When higher intensities were used the low frequency components of the chirp stimulate high CF neurons even at 40 dB HL due to basal ward spread; so the early low frequency signal components in the chirp super imposes with the later activity from the mid and high frequencies (Feobel & Dau, 2003; Petoe, Bradley, & Wilson, 2010). Additionally, each cycle of the chirp stimuli will excite a broader area of the cochlea at higher levels, resulting in some overlap and consequent desynchronization. Therefore, the comparative advantage

in evoked amplitudes given by chirps reduces with increasing stimulus intensity (Elberling & Don , 2008).

- ✓ **Within channel attraction:** Transfer functions of the cochlear filters exhibit phase dispersion in the form of frequency ‘glides’ (de Boer and Nuttall, 1997) which have been reported in basilar membrane vibrations and auditory nerve firing rates. These glides have complex behavior; increasing or decreasing in instantaneous frequency dependent on stimulus frequency (Carney, McDuffy, & Shekhter, 1999; Tan & Carney, 2003).

Rising-frequency chirps are designed to compensate for cochlear transport time delays between frequency channels but do not compensate for within-channel responses glides. In fact, a direct consequence of the coupling between channels is that the impulse responses within channels are much longer for rising-frequency chirps than for clicks. The asymmetry of the mechanical response imposes a physical limit to which one can simultaneously decrease the temporal dispersion of the impulse responses and the time delays between frequency channels (Uppenkamp, Fobel, & Patterson, 2001) Therefore, it is not possible to create a stimulus that compensates both for cochlear transport time differences across frequency and for the phase curvature in the individual auditory filters. Hence some other stimuli have to be used to overcome with all the issues.

Narrowband chirps (NB Chirps)

Narrowband chirps (NB Chirps) are octave-band limited chirp stimuli centered at 0.5, 1, 2 and 4 kHz. Narrow band chirps have got many advantages.

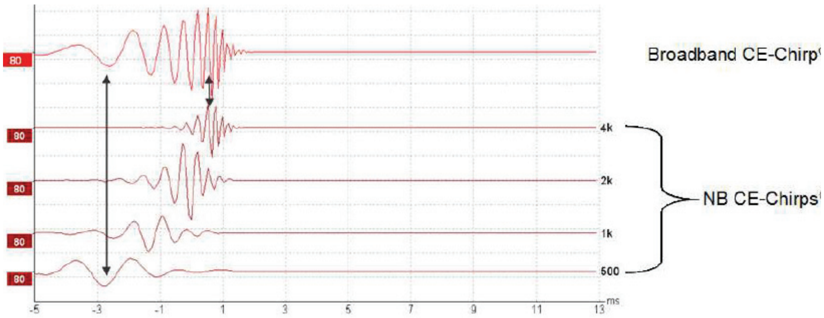

Figure 2.2 NB CE-Chirp envelops in relation to the Broadband CE-chirps. Adapted from Interacoustics, 2012

Like the broadband chirp, the NB chirp ABR in adults has amplitude that is substantially larger than its conventional tone pip counterpart (Elberling, 2011; Interacoustics, 2012). The larger response to chirp stimuli could be the result of a number of mechanisms. The chirp is designed with a delay compensation built into the octave band filter and a wider bandwidth than the tone pip (Gotsche-Rasmussen, Poulsen, & Elberling, 2012) that will increase the synchronization of the nerve fiber activity over a greater area of the basilar membrane, thereby producing a larger response. Larger amplitude ABRs (typically double the response) makes the recording faster and allows easy detection of thresholds, even at low intensity levels. It can be present at lower levels than tone pips. The effect might be expected to be more apparent at the lower frequency in which, the longer stimulus rise time of the tone pip leads to a less well synchronized neural discharge. This should allow frequency-specific ABR tests to be acquired in a time closer to that of click ABR tests.

The NB chirps allows for shorter test times in case of infants. Ferm, Lightfoot and Stevens (2013) evaluated the ABR amplitudes, test time, and estimation of hearing threshold using frequency specific chirp and tone pip in newborns. They found that chirps are a viable alternative stimulus to tone pips when completing diagnostic assessment of newborns. The amplitude, and therefore the signal to noise ratio, of the responses evoked by these stimuli, is comparable to those produced by tone pips. This allows shorter test times in the majority of cases when testing newborns. Rodrigues et al. (2013) compared auditory brainstem responses (ABRs) obtained by tone burst and narrow band CE-chirp in young infants. They found that the narrow band CE-chirp stimulus generates shorter ABR latencies than the tone burst stimuli. So as the frequency decreases, so does the latency. In addition, narrow band CE-chirp stimulus generates higher ABR amplitudes at 500, 1000, 2000 and 4000 Hz, except at high levels (80 dBnHL), where the tone burst stimuli amplitudes are greater.

Thus, literature suggests that broad-band chirp stimulus might not be a useful objective indicator for threshold estimation since it doesn’t provide frequency specific information. So the present study aimed to establish normative using narrow-band chirp ABR to verify the frequency specificity of NB-chirps. All these studies done with chirp stimuli were focused on normal cochlear processing and neural synchrony and there were no reports in literature regarding narrow-band chirp ABR in cochlear pathology. Thus the present study aimed to estimate hearing thresholds in cochlear pathology as well and to compare narrow band chirp evoked ABR thresholds with behavioral thresholds for normal and cochlear hearing loss individuals in order to correlate the frequency specificity of NB-Chirps. Most of the work comparing the amplitudes of the tone pip and chirp stimuli has been carried out in infants so it is important to extend this work in adult population using narrow-band chirp stimuli.

Chapter 3

Method

The purpose of the present study was to see the frequency specificity of narrow band chirp evoked ABR obtained at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz and its correlation with behavioral thresholds in individuals with normal hearing sensitivity and in those with cochlear hearing loss. The study also aims at establishing normative for NB-chirp ABR in adults.

Participants.

Two groups of subjects were considered for the study:

- Group I: consisted of 22 individuals with normal hearing sensitivity. The mean age was 20.5 years within an age range of 18-35 years.
- Group II: consisted of 19 individuals with sloping sensory neural hearing loss subdivided into mild and moderate categories. The mean age for individuals with mild hearing loss was 40.14 years with an age range of 29-47 years and for those with moderate hearing loss, the mean age was 33.36 years with an age range of 20-47 years.

Participant selection criteria.

Group I: individual with normal hearing

- Case history: A detailed case history was taken for each participant in order to make sure that they don’t have any symptoms of reduced hearing sensitivity.

- Air conduction thresholds were less than or equal to 15 dB HL in the octave frequency range of 250Hz to 8000 Hz and the bone conduction thresholds ≤ 15 dB HL for octaves frequencies from 250 to 4000 Hz.
- All the subjects had 'A' type tympanogram and acoustic reflexes were within normal limits indicating normal middle ear function.
- Speech identification scores (SIS) were >90%.
- None of them had any history of otological symptoms (ear pain, ear discharge & tinnitus) or retro cochlear pathology or any kind of central nervous system involvement.
- Consent was taken in prior from all the participants for their willingness to participate in the study.

Group II: individual with cochlear hearing loss hearing loss.

- Case history: A detailed case history was taken for each participant in order to make sure that they don't have any symptoms of retro-cochlear pathology.
- Individuals with sloping sensory neural hearing loss, with a pure tone average of less than 60 dB and an air bone gap of less than 10 dB across the frequencies 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz were considered for the study.
- Configuration of slope was operationally defined in terms of decrement in hearing threshold by 5 - 12 dB per octave from 250 to 8000 Hz.
- All of them had 'A' type tympanogram with present, elevated or absent of acoustic reflexes, indicative of no middle ear pathology.
- Speech identification scores were proportionate to their degree of hearing loss.

Table 3.1 Pure tone threshold at four audiometric frequencies for individuals with hearing impairment

Sl. no	***Mild hearing loss***				***Moderate hearing loss***			
	500 Hz	**1000 Hz**	**2000 Hz**	**4000 Hz**	**500 Hz**	**1000 Hz**	**2000 Hz**	**4000 Hz**
1.	25	30	35	50				
2.	20	30	35	45				
3.	20	30	35	45				
4.	20	25	35	45				
5.	15	20	30	40				
6.	20	25	35	55				
7.					25	40	55	670
8.					40	50	55	65
9.					40	45	50	60
10.					40	50	65	70
11.					35	55	65	75
12.					40	45	50	60
13.					40	45	50	60
14.					40	50	50	75
15.					40	45	50	65
16.					35	45	60	70
17.					30	40	50	65
18.					45	55	65	70
19.					40	50	55	65
Mean threshold	20	26.66	34.16	46.66	31.50	47.30	55.38	66.92

Equipments.

The following instruments were used for the study:

1. Maico MA-53 double channel clinical audiometer calibrated as per ANSI S3.6 (1996) standards coupled with acoustically matched TDH 39 headphones housed in MX-41AR ear cushions was used for estimating hearing thresholds across frequencies. A radio ear B-71 bone vibrator was used to estimate the bone conduction thresholds.
2. Calibrated GSI - Tympstar middle ear analyzer was used for tympanometry and both ipsilateral and contralateral reflex testing.
3. Inter acoustics Eclipse EP-25 was used for recording of chirp evoked ABR (which was calibration as per IEC 60645-3 standards).

Testing Environment.

All the behavioral as well as electrophysiological tests was carried out in well illuminated sound treated two room situation, with the ambient noise levels in the permissible limits as per the guidelines by ANSI S3.1 (1991).

Test Stimuli.

Octave-band limited Chirp stimuli developed by Elberling (2011) and Interacoustics (2012) were used for the testing.

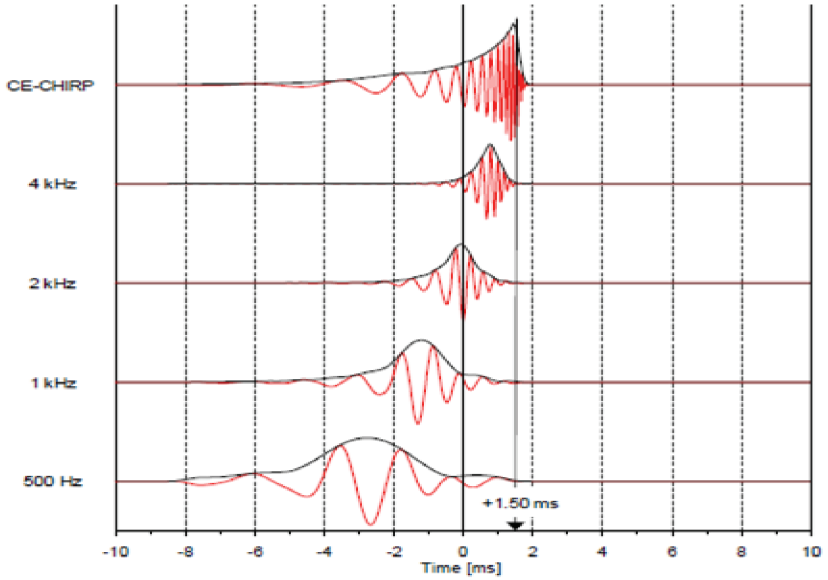

Figure 3.1 The timing of the different stimuli relative to the start of normal data acquisition

Narrow band CE-chirps were formed by decomposing the broadband CE-Chirps into four frequency bands with the center frequencies 500, 1000, 2000, and 4000 Hz. The design of NB-chirp assumes delay compensation built into the octave band filters. The delay compensation for different frequency bands were designed in such a way that their temporal references (0 ms) for lower frequencies corresponded to the estimated time of arrival of the 8000 Hz component in the cochlea which reduces the arrival time for all the frequency components. The filtered frequency bands provide a better synchronization of neural response and, consequently results in large amplitude responses.

NB-chirps centered at 500 Hz, 1 kHz, 2 kHz & 4 kHz were used to establish hearing threshold at mentioned frequencies which were readily available with Interacoustics EP-25 equipment.

Procedure.

The testing was carried out in two phases for both study and control group.

Phase I: Hearing screening, diagnostic evaluation and recording of narrow band chirp ABR for individuals with normal hearing.

The phase I consisted of hearing screening for individuals with normal hearing and diagnostic evaluation for hearing impaired along with recording of narrow band chirp ABR for individuals with normal hearing

Pure tone audiometry.

Pure-tone thresholds were obtained at octave frequencies between 250 Hz to 8000 Hz for air conduction and between 250 Hz to 4000 Hz for bone conduction through modified Hughson Westlake procedure (Carhart & Jerger, 1959). This had enabled to find out the hearing threshold in participants of Group I (which was ≤ 15 dBHL for octaves frequencies from 250 to 8000 Hz) and for those in Group II (which was between 26 dBHL to 70 dBHL). Mild hearing loss was defined for pure tone averages that ranged from 26 dBHL to 40 dBHL and moderate hearing loss was defined for pure tone averages that ranged from 41 dBHL to 55 dBHL (Clark, 1981).

Speech audiometry.

Speech identification scores were obtained for bi-syllabic PB words (Yathiraj & Vijaylakshmi, 2005) at 40 dBSL with reference to speech recognition thresholds for each individual. Obtained SIS scores were >70% in the test ear for mild hearing loss and >55% for moderate hearing loss.

Immittance:

Immittance audiometry was carried out with a probe tone frequency of 226 Hz at 85 dBSPL. Ipsilateral and contralateral acoustic reflexes thresholds was measured for 500, 1000, 2000, and 4000 Hz to rule out any middle ear pathology for both the group of participants. A significant change of admittance value of 0.05 ml was considered as a presence of reflex.

NB-Chirp ABR recording.

- Testing was carried using NB-Chirps centered at 0.5, 1, 2 and 4 kHz.
- The clients were made to sit on a reclining chair. The skin surface at the two mastoids (M1, M2), and forehead (Fz and Fpz) was cleaned with skin abrasive, to obtain skin impedance of less than 5 KΩ for all electrodes. The electrodes were placed with the help of skin conduction paste and surgical plaster was used to secure them tightly in the respective places. Participants were instructed to relax and refrain from extraneous body movements to minimize artifacts. The testing was done monaurally.
- For threshold estimation, the testing was started at higher intensities and gradually it was reduced in 10 dB steps at supra-thresholds and in 5 dB steps near thresholds using bracketing method.

- When there was a response obtained at 30 dBnHL the intensity level of NB-chirp was reduced in 10 dB steps until no response was observed. Once no response was observed, the intensity was then increased in 5 dB steps till a detectable ABR could be obtained. The minimum intensity level at which a detectable ABR could be identified was considered as NB-Chirp ABR threshold.
- At each level ABR was recorded twice to see the reproducibility of the waveform. All recording for threshold estimation were carried out at the presentation rate of 30.1/sec.

Table 3.2 Stimulus and acquisition parameters for NB-chirp ABR

Stimulus parameters		***Acquisition parameters***	
Stimuli	NB-chirps (0.5, 1, 2 and 4kHz	***Electrode placement***	Inverting-M1/M2 Non-inverting-Fz Ground-Fpz
Intensity	Variable for threshold estimation	***Mode of stimulation***	Ipsilateral
Polarity	Rarefaction	***Filter setting***	100-3000Hz
Repetition rate	30.1/sec	***Notch filter***	On
Transducer	ER-3A insert receiver	***Impedance***	Intra electrode impedance <5k Ω Inter electrode impedance <3k Ω
		Artifact rejection level	40 %
		Gain	1,00,000 times
		No. of channels	single
		Total no. of sweeps	1500
		Replicability	2 times
		Analysis time	15msec

Phase II: Recording of narrow band chirp ABR for individuals with hearing loss

- Testing was carried using NB-Chirps centered at 0.5, 1, 2 and 4 kHz.
- The clients were made to sit on a reclining chair. The skin surface at the two mastoids (M1, M2), and forehead (Fz) was cleaned with skin abrasive material, to obtain skin impedance of less than 5 KΩ for all electrodes.
- Initially the signal was presented at supra threshold and was reduced in 10 dB steps until no response was observed. Once no response was observed, the intensity was increased in 5 dB steps till a detectable ABR could be obtained. The minimum intensity level at which a detectable ABR could be identified was considered as NB-Chirp ABR threshold. At each level ABR was recorded twice to see the reproducibility of the waveform.

3.2 Analysis of waveforms.

In order to achieve the goal, qualitative as well as quantitative analysis were done for each subject in both the groups. Qualitative analysis was based on visual inspection of wave V for 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz across different intensities, ranging from higher to lower levels. Quantitative analysis was done by marking absolute latency of V peak across different intensities. All the waveforms recorded were given to two qualified Audiologists for both qualitative and quantitative analysis. The peaks which were marked by both the Audiologists were taken for further analysis. Absolute latencies were measured for each of the identified peak. It was defined in ms, between onset of stimulus and the appearance of V peak (Folsom & Abdala, 1995). The obtained data's were tabulated for statistical analysis using commercially available Statistical Package for the Social Sciences (SPSS), version 17.

Chapter 4

Results and Discussion

The present study was designed to validate the frequency specificity of NB-chirps by comparing the ABR thresholds evoked by NB-chirps, with behavioral thresholds in individuals with normal hearing and those with cochlear hearing loss and to establish normative for NB-chirp ABR in adults. The specific objectives made were 1) To find the correction factor for converting ABR nHL (normal hearing level) thresholds which were obtained using NB-chirps to eHL (estimated true hearing level) threshold in order to establish normative for NB-chirp evoked ABR, 2) To find the correlation between behavioral thresholds and NB CE-chirp ABR thresholds obtained using frequency specific chirps for individuals with normal hearing sensitivity and those with cochlear hearing loss and to validate the clinical utility of this stimulus and 3) To determine latency-intensity functioning for NB-chirp evoked ABR wave V in individuals with normal hearing and in cochlear hearing loss. The statistical analysis was carried out using SPSS, version 17. The independent variables considered were clinical group (individuals with normal hearing and those with cochlear hearing loss), type of stimulus used in the testing and, frequency and intensity of the stimulus. The dependent variables considered were the latency and estimated hearing thresholds for NB-chirp stimulus.

The following statistical tests were carried out in the present study.

1. Descriptive statistics (mean) was calculated to find the correction factor for converting nHL to eHL thresholds in individuals with normal hearing at four audiometric frequencies including 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.
2. Karl Pearson’s product-moment correlation coefficient was done to find the correlation between behavioral thresholds obtained via pure tone audiometry at

500 Hz, 1 kHz, 2 kHz and 4 kHz and NB CE-chirp ABR thresholds obtained using frequency specific chirps of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz for individuals with normal hearing and those with cochlear hearing loss (sub grouped in to mild and moderate categories).

3. Descriptive statistics was carried out to obtain mean and standard deviation of wave V latencies for different intensity levels, elicited by NB-chirps at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz in individuals with normal hearing, mild and moderate sensory neural hearing loss.

Results of the present study are discussed under the following headings.

- The relationship between behavioral (HL) and NB-chirp ABR (nHL) thresholds for both the groups.
- Correlation between behavioral (HL) and NB-chirp ABR (HL) thresholds in individuals with normal hearing and those with cochlear hearing loss including the subgroups of mild and moderate category.
- Latency - intensity functioning computed for NB-chirp evoked ABR wave V in individuals with normal hearing and in cochlear hearing loss.

4.1 The relationship between behavioral (HL) and NB-chirp ABR (nHL) thresholds for both the groups.

The mean thresholds obtained for NB-chirp ABR and pure tones are depicted in the Table 4.1. The difference between the two were calculated and rounded to nearest 1dB.

Table 4.1 Mean and standard deviation for pure tone thresholds and NB-chirp ABR thresholds at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz for individuals with normal hearing

Tests		***500Hz***	***1000Hz***	***2000Hz***	***4000Hz***
NB-chirp ABR thresholds (nHL)	Mean	21.81	22.04	14.54	12.95
	SD	05.88	07.01	04.85	05.70
Behavioral thresholds(HL)	Mean	00.90	02.72	01.36	05.22
	SD	03.32	04.00	03.83	04.35
Correction factor(HL)/difference in scores		20.91	19.32	13.18	07.73

Prediction of NB-chirp ABR thresholds (HL) for individuals with normal hearing and those with hearing loss.

NB-chirp ABR thresholds (HL) were computed by simple subtraction method from the mean difference scores obtained in individuals with normal hearing. The obtained correction values were 20.91 at 500 Hz, 19.32 at 1000Hz, 13.18 at 2000Hz and 7.73 at 4000Hz. Calculated scores were later rounded to nearest 1dB.

Table 4.2 Predicted NB-chirp ABR thresholds in individuals with normal hearing

Tests	***500Hz***	***1000Hz***	***2000Hz***	***4000Hz***
NB-chirp ABR mean thresholds (nHL)	21.81	22.05	14.54	12.95
Correction factor(HL)	21.00	19.00	13.00	08.00
NB-chirp ABR mean thresholds(HL)	00.81	03.04	01.54	04.95
Behavioural thresholds(HL)	00.90	02.72	01.36	05.22
Mean difference b/w ABR & behavioural thresholds (HL)	00.09	00.32	00.18	00.27

As shown in Table 4.2, in individuals with normal hearing, NB-chirp ABR thresholds closely correlated with behavioral thresholds across all the frequencies.

The mean difference scores between NB-chirp ABR and behavioral thresholds were greater at higher frequencies; that is, at 4000Hz the obtained difference was 0.27 dBHL. A gradual decline in the difference between the scores was observed with decrease in frequency; that is, at 2000 Hz obtained difference was 0.18; at 500 it was 0.09. But, at 1000 Hz the difference was higher (0.32) than other frequencies.

When estimating hearing thresholds using the ABR, it is important that responses are frequency specific and are as close to the behavioral pure-tone hearing thresholds as possible. Studies have been conducted to evaluate the proximity of different stimulus (like clicks and tone bursts) evoked ABR thresholds with behavioral thresholds. Bellman, Barmand and Beagley (1984) found a difference of 19 dBHL between the click evoked ABR and the mean pure tone thresholds at 1000 Hz, 2000 Hz and 4000 Hz in individuals with normal hearing sensitivity. Vander, Brocaar and Zanten (1987) found a difference of 11 dB between click ABR and mean pure tone thresholds of 2000 Hz and 4000 Hz. Vijay (2004) investigated the proximity of tone burst ABR with behavioral thresholds and found the difference of 25 dBHL at 500 Hz, 16.30 dBHL at 2000 Hz and 13.40 dBHL at 4000 Hz in individuals with normal hearing.

ABR-recorded using NB chirp in the present study provided frequency specific close approximation with behavioral thresholds as shown in the Table 4.1. Even though, literature mentions that tone burst give frequency specific responses compared to click evoked ABRs, the correction factor obtained using NB chirp in the present study is relatively lesser in comparison with that obtained using tone burst ABR at the studied frequencies. Hence NB chirp proves to be a better stimulus for the purpose of estimating ABR thresholds.

Hearing impaired individuals were sub-grouped in to mild and moderate categories. Six individuals in mild and 13 individuals in moderate category were included. NB-chirp ABR thresholds for hearing impaired individuals were estimated based on the mean differences obtained from NB-chirp ABR (nHL) to behavioral thresholds (HL), at different frequencies in individuals with normal hearing.

Table 4.3 NB-chirp ABR thresholds in individuals with mild hearing loss

Tests	***500Hz***	***1000Hz***	***2000Hz***	***4000Hz***
NB-chirp ABR thresholds (nHL)	43.33	44.16	49.16	59.16
Mean difference (HL	21.00	19.00	13.00	09.00
Predicted mean thresholds for NB-chirp ABR (HL)	22.33	25.16	36.16	51.16
Behavioural thresholds(HL)	20.00	26.66	34.16	46.66
Difference b/w ABR & behavioural threshold(HL)	02.30	01.50	02.00	04.50

It can be observed from the table that, NB-chirp ABR thresholds closely correlated with behavioral thresholds across all the frequencies, for individuals with mild hearing loss. The mean difference scores between NB-chirp ABR and behavioral thresholds were higher at two frequencies; that is, at 4000Hz the obtained difference was 4.5 dBHL and at 500 Hz the difference was 2.3 dBHL; but, for 2000 Hz, the obtained difference was only 2 dBHL and at 1000 Hz, the difference was 1.5dB HL.

Table 4.4 NB-chirp ABR thresholds in individuals with moderate hearing loss

Tests	***500Hz***	***1000Hz***	***2000Hz***	***4000Hz***
NB-chirp ABR thresholds (nHL)	56.92	62.69	67.30	75.00
Mean difference (HL)	21.00	19.00	13.00	09.00
Predicted mean thresholds for NB-chirp ABR(HL)	35.92	43.69	47.95	67.00
Behavioural thresholds(HL)	37.69	47.30	55.38	66.92
Difference b/w ABR & behavioural threshold(HL)	01.77	03.61	07.43	00.08

As shown in Table 4.4, in subjects with moderate hearing loss, NB chirp ABR thresholds closely correlated with behavioral thresholds across all the frequencies. The difference between the scores of NB-chirp ABR and behavioral threshold was lower at 500 Hz, that is, 1.77 dBHL. It gradually increased with increase in frequency; obtained difference at 1000 Hz was 3.61 dBHL and for 2000 Hz it was 7.43 dBHL. But, at 4000 Hz the difference was only 0.08 dBHL.

As discussed above, obtained difference between pure-tone thresholds and NB-chirp ABR thresholds was small across the frequencies especially at higher frequencies in individuals with normal hearing and similar findings were observed in individuals with cochlear hearing loss, (Table 4.3 and 4.4) thus the findings suggest that NB-chirp ABR is a sensitive objective tool for establishing and predicting the behavioral thresholds in individuals with normal hearing as well in those with cochlear hearing loss.

This can also be used for predicting the actual thresholds in non-organic hearing loss individuals. Morita, Masanobu and Keiji (2010) studied the need for objective assessment in 47 pediatric clients in the age range of 6-18 year who were diagnosed with non-organic hearing loss based on the symptoms reported by them. To confirm the diagnosis objective assessment was carried out including OAE and ABR testing. Results indicated discrepancies between subjective and objective assessment (in both OAE and ABR). Since OAE’s gets contaminated by several other factors which in turn reduce the sensitive of OAE’s thus, ABR which can provide optimum frequency specific responses, was recommended as an objective tool to rule out any non-organic hearing loss. Since NB-chirp ABR is proven to correlate well with behavioral thresholds, it can be effectively used in order to fulfill the above recommended need.

4.2 Correlation between NB-chirp ABR thresholds and behavioral thresholds across frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

Since NB-chirp gives close approximation with behavioral thresholds, Karl Pearson's product-moment correlation coefficient was applied, to find out the correlation between the two values across different frequencies.

Within group comparison.

4.2.1 Correlation between NB-chirp ABR thresholds and behavioral thresholds in normal hearing individuals.

Table 4.5 Correlation across different frequencies in individuals with normal hearing

	Pure tone thresholds at 500Hz	***Pure tone thresholds at 1000Hz***	***Pure tone thresholds at 2000Hz***	***Pure tone thresholds at 4000Hz***
500 NB-chirp	.581**			
1000 NB-chirp		.810**		
2000 NB-chirp			.801**	
4000 NB-chirp				.820**

**p<0.01

From the Table 4.5 it can be observed that there is positive correlation between the pure tone thresholds and NB-chirp evoked ABR thresholds in individuals with normal hearing.

The degree of correlation varied across frequencies. Though positive, correlation was relatively lesser at lower frequencies compared to higher frequencies especially at 500 Hz, where r (22) =.581 at the significance level of $p<0.01$ which was interpreted as moderate correlation between NB-chirp evoked ABR thresholds and behavioral thresholds. Whereas, at mid and higher frequencies including 1000Hz, 2000 Hz and 4000 Hz, calculated r value was ≥ .80, at the significance level of p<0.01; which was interpreted as presence of very strong correlation between the two variables.

NB-chirps were designed with a delay compensation built into the octave band filter which increases the synchronization of the nerve fiber activity over a greater area of the basilar membrane in order to compensate for the travelling wave delay. (Elberling, 2011; Gotsche-Rasmussen et al, 2012). The rapid frequency delay characteristic required to compensate for the cochlear delay limits the frequency specificity of chirps especially at lower frequencies (500Hz) where rapid compensation needs to be accomplished within fraction of seconds considering the fact of NB-Chirp design. This could be the probable reason for relatively lesser correlation at this frequency.

4.2.2 Correlation between NB-chirp ABR thresholds and behavioral thresholds in mild hearing loss individuals.

Table 4.6 correlation across different frequencies in individuals with mild hearing loss

	Pure tone thresholds at 500Hz	***Pure tone thresholds at 1000Hz***	***Pure tone thresholds at 2000Hz***	***Pure tone thresholds at 4000Hz***
500 NB-chirp	.902**			
1000 NB –chirp		.815**		
2000 NB-chirp			.920**	
4000 NB-chirp				.947**

**p<0.01

From the table it can be observed that there is high positive correlation present across all the frequencies between behavioral thresholds and NB-chirp evoked ABR thresholds; calculated r (6) was $\geq .80$, across all the frequencies at the significance level of p<0.01.

4.2.3 Correlation between NB-chirp ABR thresholds and behavioral thresholds in moderate hearing loss individuals.

Table 4.7 correlation across different frequencies in individuals with moderate hearing loss

	Pure tone thresholds at 500Hz	***Pure tone thresholds at 1000Hz***	***Pure tone thresholds at 2000Hz***	***Pure tone thresholds at 4000Hz***
500 NB-chirp	.571**			
1000 NB –chirp		.667**		
2000 NB-chirp			.833**	
4000 NB-chirp				.820**

**p<0.01

From the table 4.7 it can be observed that positive correlation was present between pure tone thresholds and NB chirp evoked ABR thresholds across different frequencies. Correlation was relatively lower at low frequencies compared to higher frequencies. At 500 Hz, r (13) = 0.571 and at 1000 Hz, r (13) = 0.667 at the significance level of $p<0.01$, which indicated moderate correlation between NB-chirp evoked ABR thresholds and behavioral thresholds. Whereas, at higher frequencies including 2000 Hz and 4000 Hz, calculated r (13) ≥ .80, at the significance level of $p<0.01$ indicated the presence of very strong correlation between the two variables.

It is evident from the table 4.6 and 4.7 that extent of correlation between NB-chirp ABR thresholds and behavioral thresholds varied for both the groups. In individuals with mild hearing loss correlation was higher compared to those with moderate hearing loss across all the frequencies. The variations between the two groups might be attributed to relatively impair cochlear active mechanism in individuals with moderate hearing loss.

Comparison between groups.

Table 4.8 Correlation between NB-chirp ABR thresholds and behavioral thresholds at different frequencies across three groups

	500Hz	***1000Hz***	***2000Hz***	***4000Hz***
Normal hearing	.581**	.810**	.801**	.820**
Mild hearing loss	.902**	.815**	.920**	.947**
Moderate hearing loss	.571**	.667**	.833**	.820**

**p<0.01

It is evident from the table above that, NB-chirp evoked ABR thresholds correlated significantly with behavioral thresholds for individuals with normal hearing as well as for cochlear hearing loss, though the degree of correlation varied across frequencies as well as across individuals. From the above findings it can be concluded that NB-chirps can exhibit optimum frequency specific responses. Thus, it incorporates the clinical utility of NB-chirp ABR as an objective indicator for threshold estimation, especially in difficult to test population.

4.3 Latency - intensity function computed for NB-chirp evoked ABR wave V in individuals with normal hearing and in cochlear hearing loss.

4.3.1 Within group comparisons.

***a) Individuals with normal hearing*.**

NB-chirp evoked ABR latency of wave V obtained at different intensities were calculated for each frequency including 500Hz, 1000Hz, 2000Hz and 4000Hz. Latency values increased with increase in intensity of the stimuli. The mean latency values were plotted as a function of intensity.

L-I as a function of intensity.

As reported by Don, Ponton, Eggermont and Kwong (1998) there are two processes affecting latencies of ABR namely which depend upon stimulation level.

1. Cochlear filter buildup time-it is the time requires to build up impulse response at the site of activation (depends on characteristic frequency, stimulus level and amount of hearing loss).
2. Synaptic delay between inner hair cells and auditory nerve fibers.

These factors can contribute to increase in latency with decrease in intensity for NB-chirp evoked ABR in individuals with normal hearing, as it increases cochlear transport time as well as cochlear filter build up time. The prolongation of latency at low stimulus levels corresponds to the propagation time of the travelling wave along the less-functioning basal part of the cochlea at these levels which in turn results in increased latencies at lower stimulation level.

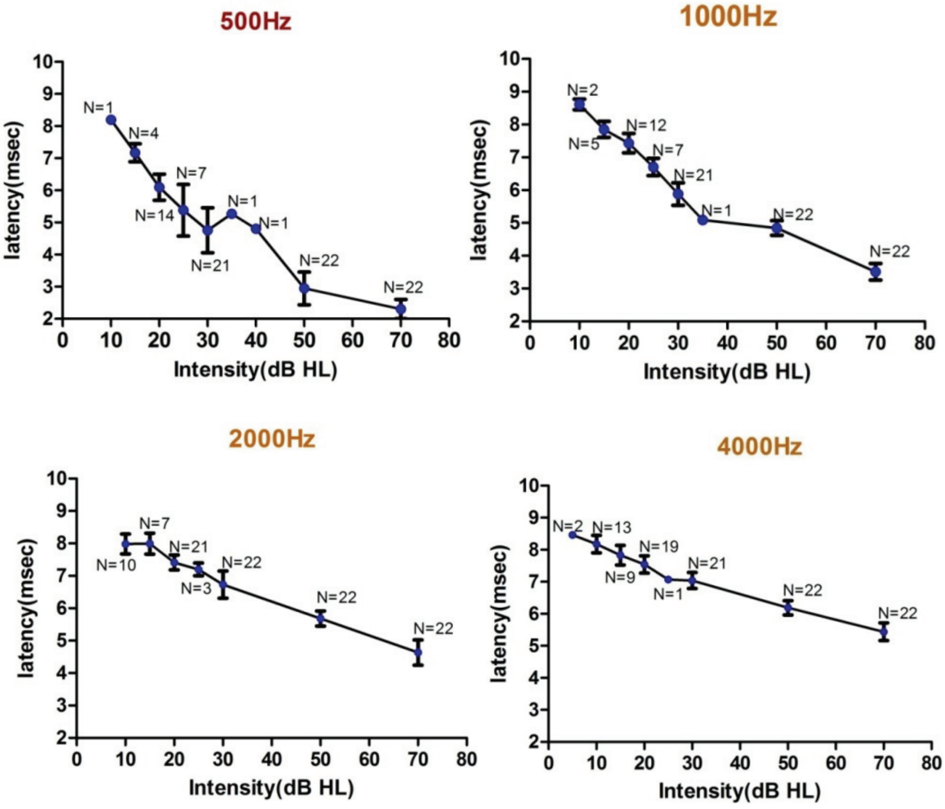

Figure 4.1 Latency-intensity function across different frequencies for individuals with normal hearing.

L-I as a function of frequency.

It can be observed from the figure 4.1 that, increase in frequency resulted in increased latency of wave V evoked by NB-chirp ABR as a function of intensity. Obtained mean latency of V peak at 70 dB for 500 Hz is 2.30 msec with standard deviation of 0.30. The latency gradually increased to 3.67 msec (SD=.676) at 1000Hz, 4.63 msec (SD=.390) at 2000Hz and 5.43 msec (SD = 0.274) at 4000 Hz. The findings of the present study are in agreement with the literature. Rodrigues et al., (2013) compared ABRs obtained by tone burst and narrow band CE-chirp at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz in 40 individuals with normal hearing sensitivity. Results showed that the lower frequency NB-chirp stimulus generated shorter ABR latencies compared to higher frequency ones. This was explained based on the design of NB-chirps. The chirp was designed with a delay compensation built into the octave band filter and a wider bandwidth (Gotsche-Rasmussen et al, 2012). Considering the fact that the 500, 1000, 2000 and 4000 Hz narrow band CE-chirp constitutes subset of the CE-Chirp, it is expected that the narrow band CE chirp latencies are shorter for the low frequency stimuli. The narrow band CE-chirps were presented in such a way that their temporal references (0 ms) for lower frequencies corresponded to the estimated time of arrival of the 8000 Hz component in the cochlea. Therefore, each of the narrow band CE-chirp has a determined timing in order to compensate for the cochlea traveling delay at centered regions of 500, 1000, 2000 and 4000 Hz which in turn reduces the arrival time for lower frequency components and results in shorter latencies for lower frequencies compare to higher frequencies.

Few studies have investigated frequency specific chirps. Bell et al. (2002) generated two chirps - the high frequency chirp (3000 - 6000 Hz) and a low frequency chirp (375 - 750 Hz) which were presented at sensation levels between 10 and 50 dB to 10 adult subjects. The results obtained in the present study are in consensus with the results obtained in this study, where wave V latency decreased as stimulus frequency decreased.

b) Individuals with cochlear hearing loss.

Individuals with cochlear hearing loss were sub grouped into mild and, moderate categories. NB-chirp evoked ABR latency of wave V obtained at different intensities, across different frequencies were calculated for both the groups separately. Latency values increased with increase in intensity of the stimuli. The mean latency values were plotted as a function of intensity.

L-I for mild hearing loss.

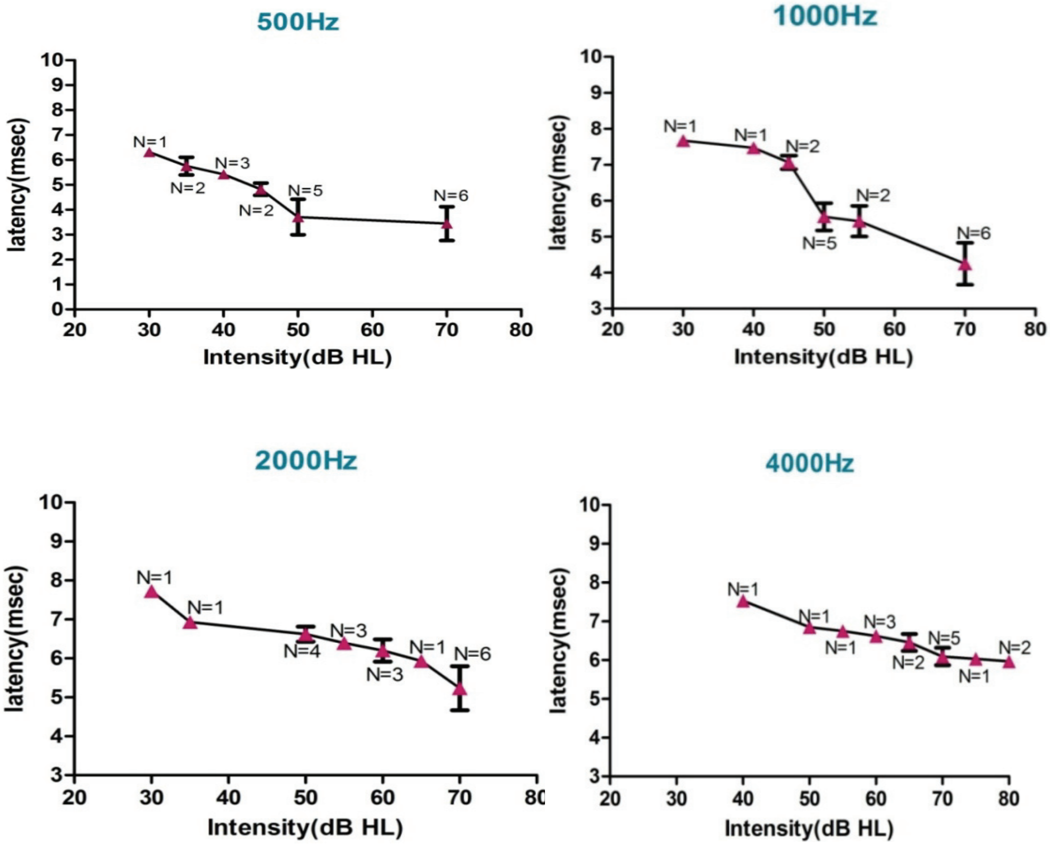

Figure 4.2 Latency-intensity functioning across different frequencies for individuals with mild hearing loss

From the Figure 4.2 it can be observed that increase in frequency resulted in increased latency of wave V evoked by NB-chirp ABR as a function of intensity. Obtained mean latency of V peak at 70 dB for 500 Hz was 3.44 msec with standard deviation of 0.677, which gradually increased to 4.24 msec (SD = 0.584) at 1000 Hz, 5.23 msec (SD = 0.567) at 2000 Hz and 6.09 msec (SD = 0.223) at 4000 Hz.

L-I for moderate hearing loss.

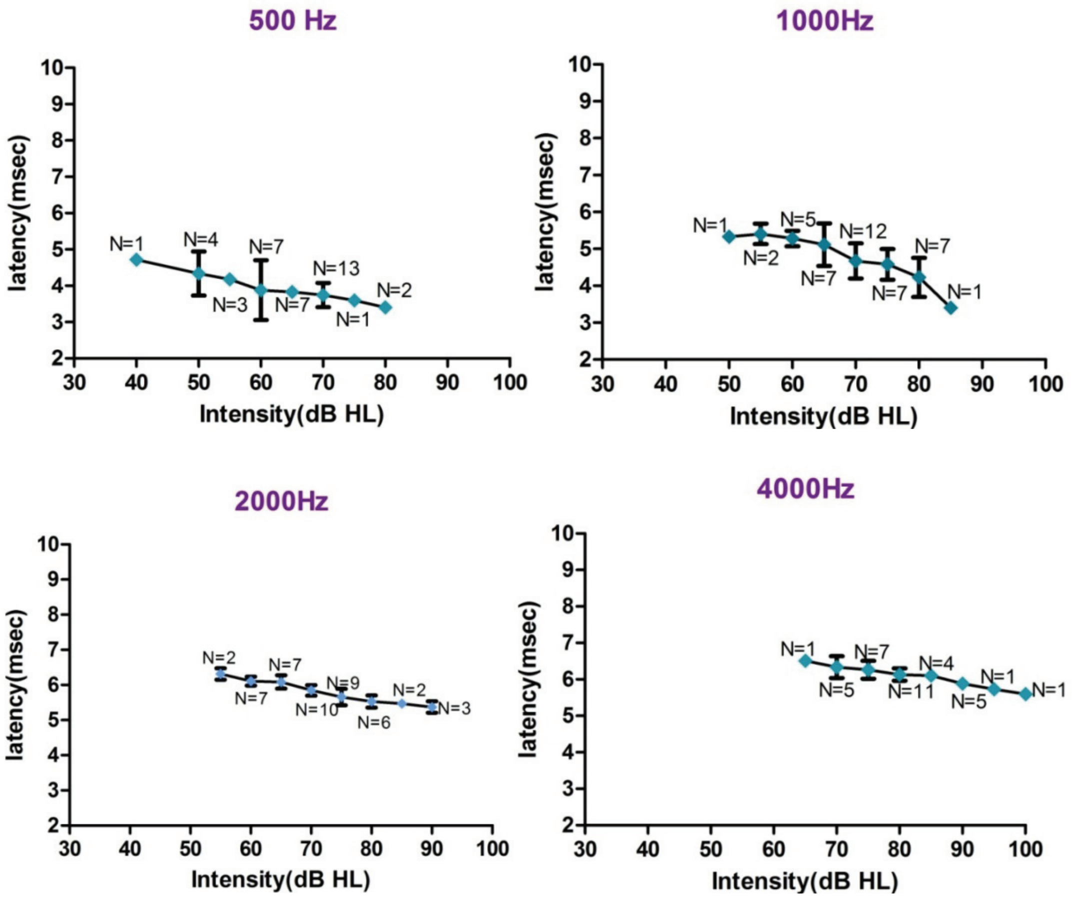

Figure 4.3 Latency-intensity function across different frequencies for individuals with moderate hearing loss

From the Figure 4.3 it can be observed that increase in frequency resulted in increased latency of wave V evoked by NB-chirp ABR as a function of intensity. Obtained mean latency of V peak at 80 dB for 500 Hz was 3.40 msec with standard deviation of 0.098, which gradually increased to 4.22 msec (SD = 0.530) at 1000 Hz, 5.53 msec (SD = 0.175) at 2000 Hz and 6.13 msec (SD = 0.170) at 4000 Hz.

It can be observed from the above Figures (4.2 and 4.3) that, as the intensity of the NB-chirp were reduced the latency of the chirp ABR increased in individuals with mild hearing loss as well as in those with moderate hearing loss. This could be attributed due to the impaired cochlear mechanism in individuals with hearing loss, which reduces the total number of nerve fibers participating in generation of action potential and results in increased latency of ABR for individuals with cochlear hearing loss. (Don et al., 1998).

Overall, it can be conclude that in all evoked potentials, synchronization of the nerve fiber firing is important to generate a large amplitude ABR waveform. Narrow Band (NB) CE-Chirp stimuli are an alternative to tone bursts which provides optimum frequency specific information along with the large amplitude ABR waveform, thus enables the easy detection of ABR peaks in individuals with normal hearing as well as in cochlear hearing loss; especially in cochlear hearing loss, where easy visual detection of waveform cannot be established due to loss of active mechanism.

Chapter 5

Summary and Conclusion

Auditory brainstem response is a widely used tool for threshold estimation and neurodiagnosis (Hall, 1992). When estimating hearing thresholds using the ABR, it is important that the responses are frequency specific and are as close to the behavioral pure-tone hearing thresholds as possible. There are several stimuli types which can be used in order to achieve this aim, which includes clicks, tone bursts, chirp, etc. Among them, the chirp attempts to optimally overcome the temporal smearing issues by compensating for the cochlear travelling wave delay, (Elberling et al., 2007) in order to provide enhanced neural synchronicity. Recently introduced narrowband chirps provide frequency specific information at the same time prevent the temporally smeared responses Elberling (2011). So, the clinical utility of narrow band chirp ABR has to be probed into. Hence, present study aimed at:

- Establishing normative for narrow-band chirp evoked ABR in adults.
- Finding the correlation between behavioral thresholds and NB-chirp evoked ABR thresholds across different frequencies (500Hz, 1000Hz 2000Hz & 4000Hz) for individuals with normal hearing sensitivity and those with cochlear hearing loss in order to validate the clinical utility of this stimulus.
- Determining latency-intensity function for NB-chirp evoked ABR wave V in individuals with normal hearing and those with cochlear hearing loss.

22 adults with normal hearing and 19 adults with cochlear hearing loss (subdivided into mild and moderate categories) participated in the study. Their behavioral thresholds NB-chirp evoked ABR were recorded for 500Hz, 1000Hz,

2000Hz & 4000Hz. The data obtained were statistically analyzed using SPSS software (version 17).

General conclusions.

The present study could establish normative for narrow-band chirp evoked ABR in adults. The correction factor across frequencies between behavioral thresholds and NB chirp evoked ABR thresholds (dBnHL) in individuals with normal hearing sensitivity, are mentioned in Table 5.1.

Table 5.1 Correction factor (dBHL) between pure tone and NB chirp ABR thresholds in individuals with normal hearing sensitivity

	500Hz	***1KHz***	***2KHz***	***4 KHz***
Correction factor	21	19	13	8

The estimated correction factor was utilized to predict the thresholds of individuals with mild sensorineural hearing loss and those with moderate sensorineural hearing loss from the nHL thresholds obtained. NB-chirp evoked ABR thresholds correlated significantly with behavioral thresholds in individuals with normal hearing and in those with cochlear hearing loss suggesting the optimum frequency specificity of NB-chirp ABR in estimating thresholds.

Further, the latency-intensity function revealed that latency of NB-chirp evoked ABR was prolonged as the intensity of the stimulus was reduced in individuals with normal hearing as well as in cochlear hearing loss. There was significant prolongation in latency with increase in degree of hearing loss, indicating the altered neurophysiological processing in individuals with cochlear hearing loss.

So, it can be concluded from the study that NB-chirp ABR can be used clinically for threshold estimation in individuals with normal hearing and in those with cochlear hearing loss. It can also be used to study the cochlear processing such as cochlear transport time and cochlear filter responses. The NB-chirp evoked ABR cannot be used for neurodiagnosis due to less frequency of occurrence of wave I and III.

Implications of the study.

1. The correction (difference between behavioral thresholds and NB chirp evoked ABR threshold) obtained for individuals with normal hearing and those with hearing loss can be used clinically to derive the reliable hearing thresholds.
2. NB-chirps are viable alternative stimulus to tone bursts especially in carrying out frequency specific threshold estimation.
3. NB chirp evoked ABR gives solid information regarding auditory status in case of difficult to test population. The study adds information to the literature.

Future research directions.

1. Study can be carried on large population with different degree, configurations and type of hearing loss.
2. The factors influencing NB chirp evoked ABR can be investigated.
3. The amplitude growth function can be studied across the frequencies and levels.

References

Agung, K., Purdy, S. C, Patuzzi, R. B, O'Beirne, G. A., & Newall, P. (2005). Rising-frequency chirps and earphones with an extended high-frequency response enhance the post-auricular muscle response. *International journal of audiology, 44*, 631-636.

ANSI S3.6. (1996). American National Standard specification for audiometers. New York. *American National Standard Institute Inc.*

American National Standards Institute. (1991). Maximum permissible ambient noise levels for audiometric test rooms (ANSI S3.1-1991). *New York: C.* Bacon.

Audiologic Guidelines for the Assessment of Hearing (2012). National Centre for Hearing Assessment and Management. CA.

Bekesy, G. V., & Wever, E. G. (1960). The Pattern of Vibrations in the Cochlea. In G.V. Bekesy (2 edition.), *Experiments in Hearing* (pp.437-521). New York, NY: McGraw-Hill.

Bell, S. L., Allen, R., & Lutman, M. E. (2002). An investigation of the use of band limited chirp stimuli to obtain the auditory brainstem response. *International Journal of audiology, 41*(5), 271-8.

Bellman, S., Barnard, S., & Beagley, H. A. (1984). A nine year review of 841 children tested by transtympanic electrochochleography. *Journal of Otolaryngology, 98*, 1-9.

Carhart, R., & Jerger, J. (1959). Preferred method for clinical determination of pure tone thresholds. *Journal of speech and hearing disorders,16,* 340-345.

Carney, L. H., McDuffy, M. J., & Shekhter (1999). Frequency glides in the impulse response of auditory nerve fibers. *The Journal of the Acoustical Society of America, 105*(6), 2384-2391.

Cebulla, M., Lurz, H., & Shehata-Dieler, W. (2014). Evaluation of waveform, latency and amplitude values of chirp ABR in newborns. *International journal of pediatric otorhinolaryngology, 78*(4), 631-6.

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *ASHA, 23*(7), 493-500.

Dau, T., Wegner, O., Mellert, V., & Kollmeier, B. (2000). Auditory brainstem responses with optimized chirp signals compensating basilar membrane dispersion. *Journal of the Acoustical Society of America*, *107*, 1530–1540.

De Boer, E. (1980). Auditory physics. Physical principle in hearing theory (1st edition), *Physics report, 62,* 87-174.

Don, M., & Eggermont, J. J. (1978). Analysis of the click-evoked brainstem potentials in man unsing high-pass noise masking. *Journal of acoustic society of America, 63*(4)*,* 1084-92.

Don, M., Kwong, B., Tanaka, C., Brackmann, D., & Nelson, R. (2005). The stacked ABR: A sensitive and specific screening tool for detecting small acoustic tumors. *Journal of audiology & neuro-otology, 10*(5), 274-90.

Don, M., Masuda, A., Nelson, R., & Brackmann, D. (1997). Successful detection of small acoustic tumors using the stacked derived-band auditory brain stem response amplitude. *American journal of otology,18*(5), 608-21.

Don, M., Ponton, C. W., Eggermont, J. J., & Masuda, A. (1994). Auditory brainstem response (ABR) peak amplitude variability reflects individual differences in cochlear response times. *The Journal of Acoustical Society of America, 96*(6), 3476-91.

Don, M., Ton, C. W, Eggermont, J. J., & Kwong, B. (1998). The effect of sensory hearing loss on coclear filter times estimated from auditor brainstem response latencies. *Journal of the Acoustical Society of America, 104*(4), 2280-9.

Elberling, C. (2011) *Selected Publications in Auditory Electrophysiology. Retrived from http://www.interacoustics-us.com/_downloads/ce-selected-publications.*

Elberling, C., & Don M. (2010). A direct approach for the design of chirp stimuli used for the recording of auditory brainstem responses. *Journal of the Acoustical Society of America, 128* (5), 2955-2964.

Elberling, C., Callo, J., & Don M. (2010). Evaluating auditory brainstem responses to different chirp stimuli at three levels of stimulation. *Journal of the Acoustical Society of America, 128* (1), 215-223.

Elberling, C., & Don, M. (2008). Auditory brainstem responses to a chirp stimulus designed from derived-band latencies in normal-hearing subjects, *Journal of the Acoustical Society of America, 124,* 3022–3037.

Elberling, C., Don, M., Cebulla, M., & Sturzebecher, E. (2007). Auditory steady-state responses to chirp stimuli based on cochlear traveling wave delay. *Journal of the Acoustical Society of America, 122* (5), 2772-85.

Ferm, I., Lightfoot, G., & Stevens, J. (2013). Comparison of ABR response amplitude, test time, and estimation of hearing threshold using frequency specific chirp and tone pip stimuli in newborns. *International Journal of Audiology, 52* (6), 419-23.

Fobel, O., & Dau, T. (2004). Searching for the optimal stimulus eliciting auditory brainstem responses in humans. *Journal of acoustic society of America, 116*(4), 2213-22.

Folsom, R. C., & Abdala, C. (1995). Frequency contribution to the click-evoked auditory brain-stem response in human adults and infants. *Journal of acoustic society of America , 97*(4), 2394-404.

Gelfand, A. S. (2007). Essentials of Audiology (2nd edition). Thieme.

Goldstein R., & Frye-osier H. (1984). *Simultaneous recording of early & late latency AEP for neonatal hearing screening or evaluation, in Nodar, Barber,evoked potentials* (2nd edition). Butterwoth.

Gorga, M. P., Kaminski, J. R., & Beauchaine, K. A., & Jesteadt, W. (1988) .Auditory brainstem responses to tone bursts in normally hearing subjects. *Journal of speech and hearing research, 31*(1), 87-97.

Gorga, M. P., Worthington, D. W., Reiland, J. K., Beauchaine, K. A., & Goldgar, D. E. (1985). *Ear Hearing, 6*(2), 105-12.

Gorga, M. P., Johnson, T. A., Kaminski, J. R., Beauchaine, K. L., Garner, C. A., Neely, S. T. (2006). Using a combination of click and tone burst-evoked auditory brain stem response measurements to estimate pure-tone thresholds. *Ear and hearing, 27*(1), 60-74.

Gorga, M. P., & Thornton, A. R. (1989). The choice of stimuli for ABR measurements. *Journal of Ear and hearing, 10* (4), 217-30.

Gotsche-Rasmussen, K., Poulsen, T., & Elberling, C. (2012). Reference hearing threshold levels for chirp signals delivered by an ER-3A insert earphone. *International Journal of Audiology*, *51,* 794-799.

Greenwood, D. D. (1990). A cochlear frequency position function for several species-29 years later. *Journal of the acoustic society of America, 87*(6), 2592-2605.

Hall, J. W. (1992). *Handbook of Auditory Evoked Responses*. Needham Heights, MA: Allyn and Bacon.

Hood, L. J. (1998). *Clinical Applications of the Auditory Brainstem Response*. San Diego, CA: Singular Publishing Group, Inc.

Interacoustics. (2012). Comparing the NB CE-chirps to tone bursts. Retrieved from http://www.interacoustics-us.com/_downloads/comparing- stimuli-toneburst-ce-chirp.pdf

Kodera, K., Yamane, H., Yamada, O., & Suzuki, J. I. (1977). The effect of onset, offset and rise-decay times of tone bursts on brain stem response. *Scandinavian Audiology*, *6* (4), 205-10.

Lutkenhoner, B., Kaufmann, G., Pantev, C., & Ross, B. (1990). Increased synchronization of the auditory brainstem response obtained by a stimulus which compensates for the cochlear delay. *Archives of Otolaryngology - Head and Neck Surgery, 2,* 157–159.

Morita, M., Suzuki, M., & Lizuka, K. (2010). Non organic Hearing loss in childhood. *International journal of pediatric otorhinolaryngology, 74* (5), 441-446.

Orsini, M. R., Hurley, M. R., Lister, J. J., & Abrams, H., (2004). A Comparison of Tone Burst Auditory Brainstem Response (ABR) Latencies Elicited With and Without Notched Noise Masking. Graduate School Theses and Dissertations.

Petoe, M. A., Bradley, A. P., Wilson, W. J. (2010). On chirp stimuli and neural synchrony in the suprathreshold auditory brainstem response. *The Journal of acoustical Society of America, 128*(1), 235-46.

Philibert, B., Durrant, J. D., Ferber-Viart, C., Duclaux, R., Veuillet, E., & Collet, L. (2003). Stacked tone-burst-evoked auditory brainstem response (ABR): preliminary findings. *International Journal of audiology, 42*(2), 71-81.

Picton, T. W., Ouellette, J., Hamel, G., & Smith, A. D. (1979). Brainstem evoked potentials to tone pips in notched noise. *Journal of Otolaryngology, 8,* 289-314.

Purdy, S. C., & Abbas, P. J. (1989). Auditory brainstem response audiometry using linearly and Blackman-gated tonebursts. *ASHA, 31* ,115-116.

Rodrigues, G. R., Ramos, N., & Lewis, D. R. (2013) Comparing auditory brainstem responses (ABRs) to toneburst and narrow band CE-chirp in young infants. *International journal of pediatric otorhinolaryngology, 77*(9), 1555-60.

Shera, C. A., & Guinan, J. J. (2000). Frequency dependence of stimulus-frequency-emission phase: Implications for cochlear mechanism. In H. Wada, T. Takasaka, K. Ikeda, K. Ohyama, and T. Koike (Eds.), Singapore: World Scientific Press, p. p. 381-387.

Shore, S. E. & Nuttall, A. L. (1985). High-synchrony cochlear compound action potentials evoked by rising frequency-swept tone bursts. *Journal of Acoustical Society of America, 78,* 1286–1295.

Stapells, D. R. (2000). Frequency-specific evoked potential audiometry in infants, In R. C. Seewald (Ed.) A Sound Foundation through Early Amplification. Basel: Phonak AG. pp. 13-31.

Stapells, D. R., & Oates, P. (1997). Estimation of the pure-tone audiogram by the auditory brainstem response. *Audiology and Neuro-otology, 2,* 257-280.

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., & Picton. T. W. (1981). Technical aspects of brainstem evoked potential audiometry using tones. *Ear and Hearing, 2,* 20-29.

Stapells, D. R., Gravel, J. S., & Martin, B. A. (1995). Thresholds for auditory brainstem responses to tones in notched noise from infants and young children with normal hearing or sensorineural hearing loss. *Ear and Hearing*, *16,* 361-371.

Stapells, D. R., Picton, T. W., & Durieux-Smith, A. (1994). *Electrophysiologic measures of frequency-specific auditory function.* In Jacobson J.T. (Ed.), Principles and applications in audiotory evoked potentials, pp. 251-283.

Stapells, D. R., Picton, T. W., Perez-abalo, M., Read, D., & Smith, A. (1985). Frequency specificity in evoked potential audiometry. In J. T. Jacobson (Ed.), The auditory brainstem response. San Diego: College-Hill Press, Inc, pp. 147-177).

Stapells, D. R., Picton, T.W., Durieux-Smith, A., Edwards, C. G., & Moran, L. M. (1990).

Suresh, K. (2013) Comparison of stacked tone ABR and chirp evoked ABR in normal and hearing impaired individuals. *Unpublished Disseratation,* University of Mysore, Mysore.

Tan, Q., & Carney, L. H. (2003). A phenomenological model for the responses of auditory-nerve fibers. II. Nonlinear tuning with a frequency glide. *The Journal of acoustical society of America , 114,* 2007-20.

Thresholds for short- latency auditory-evoked potentials to tones in notched noise in normal hearing and hearing- impaired subjects. *Audiology, 29,* 262-274.

Uppenkamp, S., Fobel, S., Patterson, R. D. (2001). The effects of temporal asymmetry on the detection and perception of short chirps. *The journal of hearing research, 158*(1-2), 71-83.

Vander Werff, K. R., Brown, C. J, Gienapp, B. A., & Schmidt Clay, K. M. (2005). Comparison of auditory steady-state response and auditory brainstem response thresholds in children. *Journal of the American academy of audiology, 13*(5), 227-35.

Vender Drift, J. F. C., Brocaar, M. P., & Van Zanten, G. A. (1987). The relationship between the pure-tone audiogram and click auditory brainstem response threshold in cochlear hearing loss. *Journal of audiology, 26*(1), 1-10.

Vignesh, S. S., & Barman, A. (2008). Comparison of click and chirp evoked ABR in normal and hearing impaired individuals. Students research at AIISH, *published Disseratation,* (4), 257-274l University of Mysore, Mysore.

Vijay, K. N. (2004). Comparison of Tone-ABR and ASSR in prediction of behavioral thresholds. *Unpublished Disseratation,* University of Mysore, Mysore.

World health Organization. (2013). Definition of hearing impairment. Retrieved from http://www.who.int/mediacentre/factsheets/fs300/en/ on 04.05.2014.

Wegner, O., & Dau, T. (2002). Frequency specificity of chirp-evoked auditory brainstem responses. *The Journal of acoustical society of America, 111(3).*

Yathin, M., & Vanaja, C. S. (2007). Effect of cochlear hearing loss on tone burst evoked stacked auditory brainstem responses. *Unpublished Dissertation,* University of Mysore, Mysore.

Yathiraj, A., & Vijayalakshmi, C. S. (2005). *Phonemically balanced word list in Kannada*. Developed in Department of Audiology, All India Institute of speech and hearing Mysore.