REDUCTION OF STIMULUS ARTIFACTS IN ASSR: AN INVESTIGATION OF A STIMULUS APPROACH

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ARIUUDAI NANBIP

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ALL INDIA INSTITUTE OF SPEECH & HEARING,

MANASAGANGOTHRI, MYSORE-570006.

APRIL 2007.

DEDICATED TO

MY APPA AND AMMA

&

TO MY TEACHERS

CERTIFICATE

This is to certify that this dissertation entitled **"Reduction of stimulus artifacts in ASSR: An investigation of a stimulus approach"** is a bonafide work in part fulfillment of degree of Master of Science (Audiology) of the student registration no: 05AUD005. This has been carried under the guidance of a faculty of this institute and has not been submitted earlier to any other university for award of any diploma or degree.

Dr. Vijayalakshmi Basavaraj,
Director,
All India Institute of Speech & Hearing,
Manasagangothri, Mysore-570006.

Mysore
April 2007

CERTIFICATE

This is to certify that this dissertation entitled **"Reduction of stimulus artifacts in ASSR: An investigation of a stimulus approach"** 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.

Prof. C.S. Vanaja
Professor of Audiology
All India Institute of Speech & Hearing,
Manasagangothri, Mysore-570006.

Mysore
April 2007

DECLARATION

This is to certify that this dissertation entitled **"Reduction of stimulus artifacts in ASSR: An investigation of a stimulus approach"** is the result of my own study and has not been submitted earlier to any other university for that award of any degree or diploma.

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CHAPTER 1

INTRODUCTION

Over the years, the need for the objective techniques in clinical practice has increased in the field of Audiology. This is partly because of introduction of universal newborn hearing screening. With the introduction of universal new born screening, there is a need to carry out diagnostic audiological evaluations on infants as early as possible. One such objective technique that can be used to estimate the hearing thresholds in infants is auditory steady state responses (ASSR).

Auditory steady state responses are evoked potentials whose constituent discrete frequency components remain constant in amplitude and phase over an infinitely long time period (Regan, 1989, cited in Picton, John, Dimitrijevic & Purcell, 2003). The ASSR can be elicited by amplitude, frequency or mixed modulated stimuli. The resultant response which has the same frequency as the modulation frequency is analyzed to detect the presence of a response. Since the frequency at which the response will occur is known and it does not vary over time, the responses are best analyzed in the frequency domain (Picton, John, Dimitrijevic & Purcell, 2003).

During the recording procedure ASSR is recorded in conjunction with electrical activity deriving from the brain, muscles of the face, scalp and neck and the electromagnetic fields present within the room. The measurements consider the steady state responses as 'signal' and the other undesired electrical activity as 'noise'. The assessment of signal to noise ratio and the estimate of whether the signal is significantly different from the noise are essential for the meaningful interpretation of ASSR. Different statistical tests can be used for the response detection in ASSR. Mainly two statistical procedures are used in commercially available ASSR systems; they are F-test (John, Dimitrijevic & Picton, 2001) and phase coherence method (Picton, Dimitrijevic, John & Van Roon, 2001).

In F-test procedure the system averages the response waveforms from many stimulus presentations and performs a fast Fourier transform on the averaged waveform. Then the amplitude in the frequency bin associated with the modulation frequency (signal) is compared with amplitude in the several bins adjacent to the modulation frequency (noise) using F-ratio. Response will be considered to be present if F-ratio probability is < 0.05 (John & Picton, 2000).

The basic concept of phase coherence method is that phase delay of the response is measured relative to the modulation frequency. Each sample of responses is subjected to fast Fourier transform to measure phase and amplitude of the spectral peaks. To assess phase coherence, the phase of responses at modulation frequency is plotted in polar co ordinates. The phase coherence value will vary from 0 to 1. If the sample phases are in phase with one another, high phase coherence is achieved and when the phases are random low coherence is achieved (Sininger & Cone-Wesson, 2002, cited in Katz, 2002). The probability that the response samples occurs in the same phase is tested statistically at significance level of $p< 0.01$ (Luts & Wouter, 2005).

ASSR is analyzed in frequency domain and an algorithm built in the instrument automatically determines the presence of a response. There are chances that any electrical signal/noise which has same frequency of modulation also can be detected as the response by the instrument. Gorga et al. (2004) reported of such artifacts in the ASSR measurements carried out at high intensities. Picton and John (2004); Small and

Stapells (2004) also reported of artifacts while recording ASSR at high intensity and reasoned out that one source of artifact is electromagnetic aliasing error. These studies were carried out using weighted averaging method. Name, Nambi and Vanaja, (2006) reported of artifacts while recording ASSR using phase coherence method also. The presence of artifacts at high intensities reduces the dynamic range available for testing and it becomes difficult to differentiate between individual with severe and profound hearing loss.

NEED FOR THE STUDY

Investigations have been carried out to determine the upper limit for artifact free measurements when ASSR is recorded using weighted averaging method. Name, Nambi and Vanaja (2006) determined the upper limits for artifacts free ASSR measurements for air conduction transducers for ASSR recorded using phase coherence method. The upper limit for artifact free ASSR measurements for bone conduction transducer also needs to be determined.

Picton and John (2004) used different approaches to eliminate artifacts by shifting the aliasing frequency away from the modulation frequency. These approaches include the use of different stimuli such as 'beats' which has the energy at carrier frequency ± half of modulation frequency, sinusoidally alternated amplitude modulated tone which has the energy at carrier frequency + 3/2 times of modulation frequency and carrier frequency ± half of modulation frequency and changing the A/D conversion rates. These approaches have shown to be effective in avoiding artifacts in weighted averaging method. It is not known whether these techniques will help in phase coherence method also. Another approach which can probably shift the aliasing frequency away from the modulation frequency is using a carrier frequency which is not an integer multiple of sampling frequency (Picton & John, 2004). Research needs to be done to check whether changing the carrier frequency can avoid the artifacts or enhance the dynamic range of ASSR for artifact free measurements. There is also a need to compare the occurrence of artifacts at different carrier frequencies and across the air conduction and bone conduction transducer for ASSR recorded using phase coherence method.

AIMS: The present study was designed to investigate the following aims.

- To determine the upper limits for artifact free ASSR measurements for air conduction and bone conduction transducers for ASSR analyzed using phase coherence method for conventional carrier frequencies
- To investigate if the artifact can be avoided or dynamic range of ASSR for artifact free measurements be enhanced by using the carrier frequencies which are not an integer multiple of sampling frequencies.
- To compare the percentage of individuals in whom artifacts are observed at different carrier frequencies
- To compare the percentage of individuals in whom artifacts are observed for the stimuli presented through headphone and bonevibrator.

CHAPTER 2

REVIEW OF LITERATURE

In the field of clinical Audiology threshold estimation plays very important role for diagnosis as well as rehabilitation. Either behavioral or physiological test can be used for establishing hearing thresholds. Even though the behavioral tests are preferred to physiological tests to obtain accurate estimation of threshold, it may be difficult to arrive at a diagnosis only based on behavioral methods in difficult to test population. Physiological tests will be useful while evaluating such individuals.

Auditory steady state response is one of the physiological tests developed for threshold estimation. ASSR examines the responses to sinusoidal stimuli that are modulated in amplitude, frequency, or both, amplitude and frequency modulated. The resulting responses are periodic and phase locked to the modulation frequency of the stimulus. ASSR can be obtained for wide range of modulation frequencies (Rickards, & Clark, 1994), but modulation rates around 70-100 Hz have proven to be more suitable for assessment of sedated and sleeping subjects (Cohen, Rickards & Clark, 1991).

Over the years data have begun to accumulate that suggest that ASSR threshold estimates are reasonably accurate in predicting behavioral thresholds. A number of investigators have reported that ASSR thresholds correlate well with behavioral thresholds. (Cone-wesson et al., 2002; Aoyagi et al., 1994; Luts & Wouter, 2005; Werff, Brown, Gienapp, Schmidt & Clay, 2002). Rance, Rickards, Cohen, Vidi and Clark (1995) examined the relationship between ASSR thresholds and behavioral thresholds in 60 sleeping subjects whose hearing thresholds ranged from normal to profound. They observed a strong correlation between ASSR thresholds and behavioral thresholds and the strength of the relationship increased with increasing degrees of hearing loss. Similar results have been reported by other investigators also.

Lins et al. (1996) reported that multiple auditory steady state responses predicted the behavioral thresholds of 10 adolescents with moderate hearing loss with correlation coefficients of 0.72, 0.70, 0.76 and 0.91 at 500Hz, 1000Hz, 2000Hz and 4000Hz respectively. Luts, Desloovere, Kumar, Vandermeersch, and Wouters (2004) reported that dichotic multiple ASSR thresholds also correlated well with frequency specific behavioral thresholds in 10 infants with hearing loss. The correlation values were 0.92, 0.93, 0.91 and 0.93 for the carrier frequencies 500Hz,1000Hz, 2000Hz and 4000Hz respectively.

Research has indicated that ASSR thresholds are generally 10 to 20dB higher than the behavioral thresholds (Picton, John, Dimitrijevic & Purcell, 2003). Herdmann and Stapells (2001) reported that ASSR estimated the behavioral thresholds in 10 normal hearing adults in the range of 7 to 14 dB SPL. Perez-Abalo et al. (2001) examined the relationship between multiple auditory steady state responses and behavioral thresholds in 43 children with moderate to severe hearing loss and 40 normal hearing adults. In the normal hearing subjects ASSR thresholds were on an average between 11 to 15dBHL above the behavioral thresholds. These differences were significantly less for individuals with hearing impairment.

Dimitrijevic et al. (2002) correlated the behavioral thresholds with multiple auditory steady state responses in 37 adults with sensory neural hearing loss and 14 adults with normal hearing. For air conduction measurements the difference between ASSR thresholds for mixed modulated stimuli and behavioral thresholds for pure tone stimuli were 14 ± 11, 5 ± 9, 5 ± 9,9 ±10 (in dB HL) for the 500Hz, 1000Hz, 2000Hz and 4000Hz respectively. Similarly for bone conduction the differences were 22 ± 8, 14 ± 5, 5 ± 8, and 5 ± 10 (in dB HL) for the 500Hz, 1000Hz, 2000Hz and 4000Hz respectively. Swanepoel, Schmulian and Hugo (2004) correlated dichotic multiple frequency ASSR and behavioral thresholds in 28 normal hearing subjects. The ASSR thresholds were 30-34dB above behavioral thresholds across the frequency range of 500Hz to 4 kHz.

Attempts have been made to compare the efficiency of ASSR and tone burst evoked ABR in predicting behavioral thresholds. Aoyagi et al. (1999) evaluated the reliability of ASSR and ABR in predicting the behavioral thresholds during sleep in 169 ears of 125 children with hearing impairment. The results revealed that the correlation coefficient values between ASSR and behavioral thresholds were higher when compared to values between ABR and behavioral thresholds though not to a significant degree.

Herdmann and Stapells (2003) reported that ASSR thresholds were significantly closer to behavioral thresholds when compared to ABR thresholds. ASSR accurately estimated degree and configuration of hearing loss in 31 adults with sensory neural impairment and ASSR did not under estimate the thresholds in case of steeply sloping (>30dB/octave) hearing loss also.

Name (2004) evaluated the efficacy of ASSR and tone burst ABR in prediction of behavioral thresholds in 20 normal hearing adults and in 15 ears of adult subject with cochlear hearing loss. The correlation coefficient values between tone burst ABR and behavioral threshold was 0.74, 0.84, and 0.90 for the 500Hz, 2000Hz, and 4000Hz frequencies respectively. The correlation coefficient values between ASSR and behavioral threshold is 0.49, 0.75 and 0.87 for the 500Hz, 2000Hz, and 4000Hz frequencies respectively. However this study was carried out on adults, some of whom were awake during the testing. Probably this might have lead to the more variability in threshold prediction by ASSR when compared to tone burst-ABR.

One of the major advantages of ASSR over conventional ABR is its large dynamic range which was thought to be helpful in differentiation of severe to profound hearing loss. It is possible to present ASSR stimulus of 115dBHL or greater as it uses continuous long duration signal. Rance et al. (1993) studied the efficacy of ASSR in predicting behavioral thresholds in a group of individual with severe to profound hearing loss. Results revealed that ASSR predicted behavioral thresholds within 10 dB on 96% of occasions. Ranee and Briggs (2002) examined the relationship between behavioral thresholds and ASSR thresholds in 200 children with moderate to profound hearing loss. There was a strong correlation between behavioral thresholds and ASSR thresholds with coefficient ranging from 0.81 to 0.93.

Ranee, Dowell, Rickards, Beer and Clark (1998) evaluated 108 infants and children using ABR and ASSR. ASSR predicted behavioral thresholds within lOdB 82% of the times and 95% of the times it predicted thresholds withinl5dB even though ABR was absent in these ears. ASSRs were present in ears that did not produce an ABR, suggesting that the measurements can be applied with greater degrees of hearing loss. However in some of the subjects ASSR was present even in the absence of behavioral thresholds at low frequencies (250 & 500Hz) and this was attributed to the steady state potential that may have been evoked by vibrotactile stimulation. Swanepoel, Hugo and Roode, (2004) reported that ASSR thresholds provided reliable estimations of behavioral thresholds for 10 children with severe to profound hearing loss ranging in age from 10 to

15 years and the results indicated a closer correlation between ASSR and profound behavioral thresholds than for severe thresholds. In case of severe hearing loss ASSR thresholds were on an average 6-13 dB above the behavioral thresholds and in subjects with profound hearing loss, ASSR thresholds were on an average 1 to 4dB below the behavioral thresholds. Results of these studies support the advantage of large dynamic range of stimuli used for ASSR which will help to differentiate severe to profound hearing loss. However presence of ASSR at 1 to 4dB below the behavioral thresholds in subjects with profound hearing loss indicates possibility of artifactual responses. Earlier Ranee, Dowell, Rickards, Beer and Clark, (1998) reported that presence of response at an intensity which is less than the behavioral thresholds indicates the possibility of artifacts.

Gorga, Neely, Hoover, Dierking, Beauchaine and Manning (2004) were the first to confirm the presence of artifactual ASSR at higher levels (> 95dBHL). They recorded the steady state responses in 10 individuals with profound hearing loss who did not show behavioral responses even at the maximum limit of the instrument. Small and Stapells, (2004) studied artifacts in 15 individuals with severe to profound hearing loss who did not respond to modulated stimuli behaviorally. The results indicated that both air conduction and bone conduction transducers produced spurious responses and they hypothesized that the artifact might be the result of electromagnetic aliasing error and the physiological artifacts are of vestibular origin. Picton and John (2004) also reported the presence of artifacts in 12 normal hearing subjects ranging in age from 21 to 29 years. The artifacts were reduced when analog to digital conversion rates were increased or high frequency components in the EEG signal were attenuated. These results confirmed the presence of electromagnetic aliasing artifacts while recording ASSR. All these investigators recorded artifacts using an instrument which uses weighted averaging method to detect the responses. Name, Nambi and Vanaja (2006) reported artifacts in 8 ears of 12 individual with profound hearing loss ranging in age from 18-30 years. They reported that artifacts occur even when phase coherence method is used to detect the responses. Further the results revealed that the upper limit for artifact free ASSR measurement for head phone is 90dBHL and for insert ear phone is 105dBHL. When weighted averaging method is used the upper limit for artifact free ASSR measurement for insert earphone is 95dBHL (Gorga et al., 2004), and for bone conduction transducer is 40dBHL (Small & Stapells, 2005).

Mechanisms of artifacts

Researchers have put forth a few hypotheses some of which are tested to explain the presence of artifacts. The responses picked up while recording ASSR will contain signal as well as noise and if the frequency of the noise matches with the modulation frequency, the instrument may consider it as a response. The sources of artifacts will be same as the sources of noise. The possible sources of artifacts include electro magnetic radiations from the stimulus or circuit and physiological noise within the subject.

Artifacts due to electromagnetic radiation: Small and Stapells (2004) hypothesized that artifacts may be induced by the stimuli used for recording ASSR. The ASSR is elicited by the envelope of signal rather than by the carrier signal but energy is present only in the carrier signal not in the envelope of the signal (Picton & John, 2004). So initially the source or mechanism of artifacts was unclear. Finally Picton and John, (2004); and Small and Stapells (2004) reasoned out that "aliasing error" causes the occurrence of artifacts in ASSR.

Aliasing occurs when the signal is sampled at a rate lower than twice its frequency. Frequency of the signal due to aliasing error is equal to absolute difference between the input frequency and its closest integer multiple of sampling frequency. The sampling frequency used in the ASSR is designed for the efficient analysis of the responses at the frequencies of modulation. For example a 500 Hz carrier tone amplitude modulated at 80 Hz would have energy at 420 Hz, 500 Hz and 580 Hz. If this energy present in EEG is being digitized at a sampling frequency of 500 Hz, an alias frequency would be 80 Hz which is exactly same as the modulation frequency. Figure 1 shows an example of aliasing error.

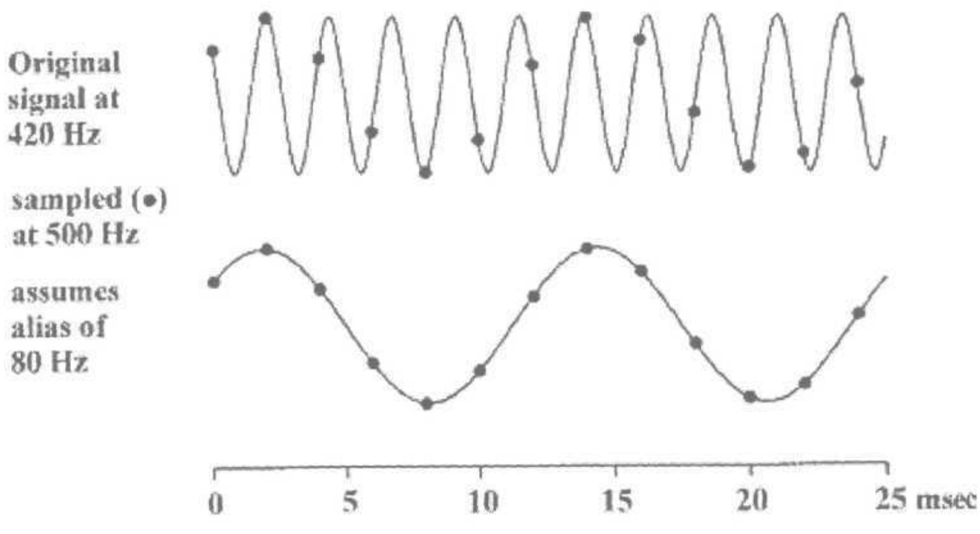

Figure 1: Graphical representation of aliasing error (adapted from Picton & John, 2004)

Another possible mechanism for electro magnetic artifacts is the leakage of currents through recording circuits that occur after the amplification of EEG signal. These are generally very small. Also the acoustic transduction of the energy should not be at the envelope frequency since it is an amplitude modulated stimuli. However, nonlinearities may occur during the leakage process and aliasing can occur if the leakage happens after the amplification / filtering and before the A/D conversion, (Picton *& John*, 2004).

Physiological artifacts: Some auditory stimuli may evoke responses from physiological generators which are not related to auditory processing. These are considered as physiological artifacts in objective assessment of hearing. Such physiological artifacts also might be present in ASSR. In literature it is reported that the vestibular end organ, saccule is sensitive for the acoustic stimulation also. Nong, Ura, and Noda (2000) reported a short latency negative responses (N3) in profound hearing loss individuals while recording ABR. They reported that saccule was the sense organ and the responses originated from the vestibular nuclei of the brainstem. There is a possibility of such artifacts during the recording of ASSR also. Small and Stapells (2004) reported that artifacts at 500 Hz might be of physiological origin. They hypothesized that, the vestibular evoked myogenic potentials (VEMP) from the inion muscle might be the origin of physiological artifacts, because of the close proximity of nape where inverting electrode was placed. Results of an investigation by Name, Nambi, and Vanaja (2006) also supported the possibility of vestibular artifacts based on latency calculations from the phase delay. The latency of the artifacts were around 3-5 msec which is similar to N3 potential seen around 3 msec in profound loss individuals reported by Nong, Ura, and Noda (2000)

Modifications to avoid aliasing artifacts

Picton and John (2004) tested some of the approaches which avoided the electromagnetic aliasing artifact. They recommended the use of different stimulus such as beats, alternating sinusoidally amplitude modulated tone, increasing the sampling rate such a way that their integer multiples are not sampling frequencies, and increasing the sampling rate to 8000 Hz which is nyquist frequency for the highest carrier frequency 4000 Hz.

(i) *Beats:* Beats are perceived when summing the two puretones which are separated by less than a critical bandwidth are presented simultaneously. The resulting frequency of stimulus will be equal to average frequency of the two pure tones and will beat at a rate of difference in the frequency of puretones (Schwartz & Taylor, 2005). For example, when two puretones of 480 Hz and 520 Hz are summed to produce beats, the resulting stimuli will be at 500 Hz and will beat at a rate of 40 Hz. These stimuli are similar to amplitude modulated tones where the rate of beats corresponds to the frequency of amplitude modulations. Since it is similar to amplitude modulated stimuli it can be used to elicit ASSR. The spectrum of the beat stimuli contains energy at carrier frequency $\pm$ half of modulation frequency. When aliasing error occurs for these stimuli, the aliasing error would be at half of modulation frequency and does not interfere while assessing the response at modulation frequency (Picton & John, 2004).

(ii) *Alternating sinusoidally amplitude modulated tone (SAM):* In alternating sinusoidally amplitude modulated tone, the polarity of the carrier is inverted in each modulation. The change in the polarity occurs in the null section of amplitude modulation stimuli which is shown in the Figure 3. This stimulus contains energy at carrier frequency $\pm$ 3/2 times of modulation frequency and carrier frequency $\pm$ half of modulation frequency. When such stimuli are used the resulting aliasing frequency will be at half of modulation frequency and at 3/2 times of modulation frequency which will be away from modulation frequency. This way aliasing frequency can be shifted away from the modulation frequency.

Figure 2: Graphical representation of alternating sinusoidally amplitude modulated tone (Adapted from Picton & John, 2004)

(iii) *Modifying the A/D rate:* According to the formula described by Small and Stapells (2004) the aliasing artifacts occur when the carrier frequency is an integer multiple of the sampling frequency. Small and Stapells (2004) reported that use of A/D conversion rate such as 1250 Hz can also shift the aliasing frequency away from the modulation frequency 1250 Hz which does not become integer multiple of conventional carrier frequencies which are generally 500, 1000, 2000 and 4000Hz. For 500Hz carrier signal this sampling frequency may not cause aliasing since it is higher than the nyquist frequency. For 1000, 2000 and 4000 Hz it may cause aliasing since it is less than the nyquist frequency but the aliasing frequency may not be at modulation frequency. Similarly Picton and John (2004) recommended use of sampling rate of 1280. Increasing the sampling rate to 8000 Hz which is nyquist frequency for the highest carrier frequency 4000 Hz will avoid the aliasing error (Picton & John, 2004)

(iv) *Changing the carrier frequency:* Another way to deflect the aliasing frequency away from the modulation frequency is changing the carrier frequency such a way that they are not integer multiple of the sampling frequency (Picton & John, 2004). Feasibility of this approach was not evaluated.

Thus review of literature shows that artifacts contaminates recording of ASSR at high intensities. There is a dearth of literature on approaches to avoid artifacts while recording ASSR at high intensities. Research is needed in this area to increase the clinical utility of ASSR.

CHAPTER 3

METHOD

The current study was aimed to investigate the occurrence of artifacts elicited while recording ASSRs. The following method was adopted to investigate the aims of the study.

Participants

Thirty individuals with profound hearing loss ranging in age from 18 to 40 years participated in the current study. ASSR was recorded from 15 participants for stimuli presented through head phone and from 15 participants for stimuli presented through bone vibrator. It was ensured that the subjects did not show any behavioral responses to mixed modulated stimuli used for recording ASSR at the presentation level used in the experiment.

Instrumentation

A calibrated two channel diagnostic audiometer Madsen OB 922 audiometer with TDH 39 headphone and radio ear B71 bone vibrator was used to estimate the behavioral thresholds at octave frequencies from 0.5 to 4 kHz.

GSI- Audera version (1.0.2.2) was used to record ASSR as well as to obtain behavioral thresholds to mixed modulated stimuli presented through headphone and bonevibrator. This software version conventionally produces the modulated stimuli at the octave frequencies from 250 kHz to 4 kHz but it also provides the option to change the carrier frequencies.

Procedure

Pure tone audiometric thresholds and behavioral thresholds to the modulated tones were measured using modified Hughson & Westlake (Carhart & Jerger, 1959) procedure. Behavioral thresholds to modulated stimuli were obtained at 500, 1000, 2000, and 4000 Hz, hereafter referred to as conventional carrier frequencies, and 522, 1022, 2022, & 4022 Hz, hereafter referred to as experimental carrier frequencies, in the current study. These measurements were carried out to ensure that the participants meet the subject selection criteria.

For recording ASSR, subjects were seated comfortably in a reclining chair and they were asked to relax or sleep. Electrode sites were cleaned using skin prepping gel. Silver chloride electrodes were used to record the ASSR using three electrode placement. For air conduction measurement inverting electrode was placed at test ear mastoid, non inverting electrode was at fore head and ground electrode was placed on the mastoid of non test ear. For bone conduction measurements non inverting electrode was placed at vertex and the site for inverting and non inverting electrodes were same as that used for air conduction measurements. It was ensured that electrode impedances were less than 5 kohms and inter electrode impedance was less than 2 kohms.

For air conduction measurements supra aural headphone was placed over the pinna and for bone conduction measurements bone vibrator was placed on the fore head. ASSR's were recorded for both conventional carrier frequencies, 500, 1000, 2000, & 4000 Hz and for experimental carrier frequencies, 522, 1022, 2022, & 4022 Hz in all the subjects. ASSR was recorded using protocol given in Table 1. Testing was initiated at the maximum limits of instrument and the intensity was varied in 5 dB steps to find out the intensity level at which artifact free ASSR measurements can be obtained. The instrument determined the presence of responses based on non random phase behavior. Response was considered as present if phase locked responses occurred.

Table 1: Protocol to record ASSR

Stimulus presentation	Single frequency, monaural	
Amplitude modulation depth	100%	
AM/FM rate	Modulation rate	Carrier frequencies
	74 Hz	500 & 522 Hz
	81 Hz	1000 & 1022 Hz
	88 Hz	2000 &2022Hz
	95 Hz	4000 &4022 Hz
Frequency modulation depth	10%	
AM / FM Phase	0°	
Calibration	HL	
Intensity	Varied	
Response detection	Phase coherence ($p < 0.01$)	

CHAPTER 4

RESULTS

The data obtained from the participants were tabulated and subjected to statistical analysis. At each frequency and for each transducer the percentage of subjects in whom artifacts were present was calculated separately. The statistical procedure 'equality of proportions' was carried out to check if there is a significant difference in the percentage of subjects in whom artifacts were observed across different frequencies and across different transducer.

Artifacts in ASSR for conventional carrier frequencies

Table 2 depicts the percentage of individuals who demonstrated artifacts at different frequencies for conventional carrier frequencies for stimuli presented through head phone and bone vibrator. It can be observed from table 2 that artifacts were present when the conventional carrier frequencies were used. The artifacts are present in all the four carrier frequencies and for stimuli presented through both the transducers.

Table 2: Percentage of subjects with artifacts for conventional carrier frequencies

Frequency	**Percentage** (%)	
	Head phone	**Bone vibrator**
500	93.3	91.6
1000	80.0	46.15
2000	*66.6*	40.0
4000	*26.6*	26.6

It can be observed from Table 2 that as the carrier frequency is increased the percentage of subjects in whom artifacts were observed decreased for both air conducted and bone conducted stimuli. It is clear from the Table 3 that there was a statistically significant difference ($p < 0.05$) between 500 & 4000 Hz, 1000 & 2000 Hz, 1000 & 4000 Hz, 2000 & 4000 Hz for stimuli presented through air conduction transducer and between 500 & 1000 Hz, 500 & 2000 Hz, 500 & 4000 Hz for stimuli presented through bone conduction transducer.

Table 3: Results of equality of proportions to compare the percentage of subjects with artifacts at different carrier frequencies within conventional carrier frequencies

Frequencies (Hz)	Z score	
	Head phone	Bone vibrator
500 & 1000	1.07	2.52*
500 & 2000	1.82	2.85*
500 & 4000	3.74*	3.51*
1000 & 2000	0.83	0.35
1000 & 4000	2.95*	1.14
2000 & 4000	2.20*	0.78

* Significant at 0.05 level.

Table 4 reveals that among conventional carrier frequencies, except at 1000 Hz equality of proportion did not reveal any statistically significant difference ($p > 0.05$) between both the transducers in terms of percentage of subjects in whom artifacts were present. Even though statistically significant difference was obtained only at 1000 Hz, the visual inspection of the data revealed that for bone conducted stimuli fewer subjects demonstrated artifacts when compared to air conducted stimuli even for 2000 Hz.

Table 4: Results of equality of proportions to compare the percentage of subjects with artifacts across the transducers

Transducer	Frequencies	Z score
AC	500	0.19
BC		
AC	1000	1.97*
BC		
AC	2000	1.46
BC		
AC	4000	+
BC		

* Significant at 0.05 level

+ Both are equal

Artifacts in ASSR for experimental carrier frequencies

In ASSR elicited using experimental carrier frequencies also subjects demonstrated artifacts but not at all the frequencies. Table 5 shows the percentage of subjects in whom artifacts were present at different frequencies for both the transducers.

Table 5: Percentage of subjects with artifacts in ASSR for experimental carrier frequency

Frequencies (Hz)	Percentage (%)	
	Head phone	Bone vibrator
522	*66.6*	33.3
1022	40.0	23.07
2022	13.5	0.0
4022	0.0	0.0

Similar to conventional carrier frequencies in experimental carrier frequencies also as the frequency of the carrier signal increased the percentage of subjects in whom artifacts were present decreased. This can obtained from the table 5. Equality of proportion test showed a statistically significant difference ($p < 0.05$) between 522 & 2022 Hz, 522 & 4022 Hz, 1022 & 4022 Hz for air conduction transducer and for bone conduction transducer significant difference ($p < 0.05$) was obtained between 522 & 2022 Hz, 522 & 4022 Hz, 1022 & 2022 Hz, 1022 & 4022 Hz.

Table 6: Results of the equality of proportions to compare the percentage of subjects with artifacts at different carrier frequencies within experimental carrier frequencies

Frequencies (Hz)	**Z score**	
	Head phone	**Bone vibrator**
522 & 1022	1.46	0.59
522 & 2022	2.99*	2.52*
522 & 4022	3.89*	2.52*
1022 & 2022	1.65	2.09*
1022 & 4022	2.75*	2.09*
2022 & 4022	1.47	+

* Significant at 0.05 level

+ Both are equal

Equality of proportion test did not show any statistical difference ($p > 0.05$) between both the transducers in experimental carrier frequencies in terms of percentage of subjects in whom artifacts were present. However visual inspection of the data showed that over all ASSR elicited for air conducted stimuli had higher percentage of subject with artifacts when compared to ASSR elicited by bone conducted stimuli except at 4022 Hz.

Table 7: Results of equality of proportions to compare the percentage of subjects with artifacts across the transducers

Transducer	**Frequencies**	**Z score**
AC	522	1.79
BC		
AC	1022	1.02
BC		
AC	2022	1.47
BC		
AC	4022	+
BC		

+ Both are equal

Comparison between ASSR for conventional and experimental carrier frequencies

Overall for experimental carrier frequencies, fewer subjects had artifacts when compared to conventional carrier frequencies across both transducers. This can be made clear by comparing the Table 2 and 5. From the comparison of two tables it can be observed that artifacts are completely avoided for 4022 Hz during both air conduction and bone conduction measurements. For 2022 Hz artifacts were absent during bone conduction measurements and number of individuals who had artifacts were minimal during air conduction measurements.

Figure 3 and 4 depicts the number individual with artifacts for both conventional and experimental carrier frequencies for air conducted and bone conducted stimuli. From the figures it is clear that less number of individuals had artifacts with experimental carrier frequency when compared to conventional carrier frequencies.

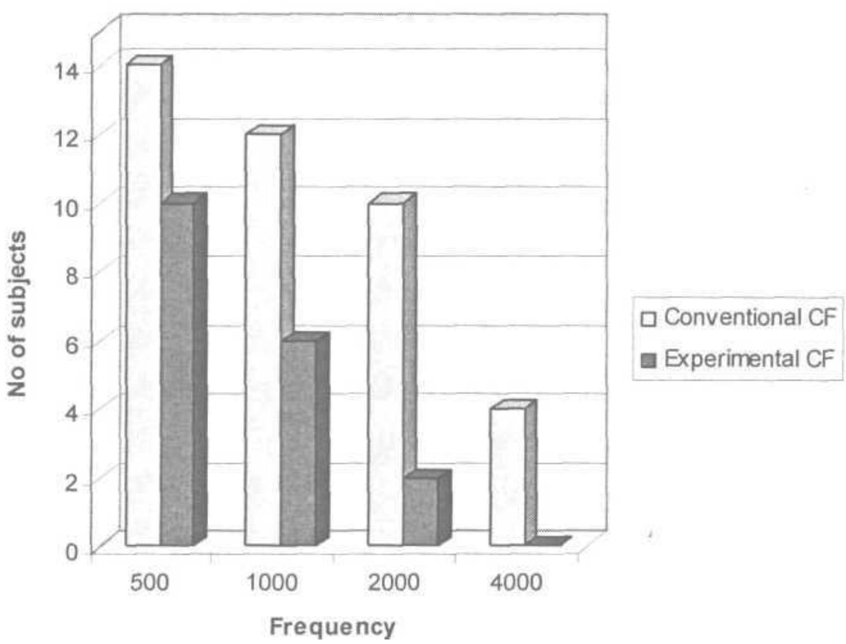

Figure 3: Number of individuals with artifacts for air conducted stimuli

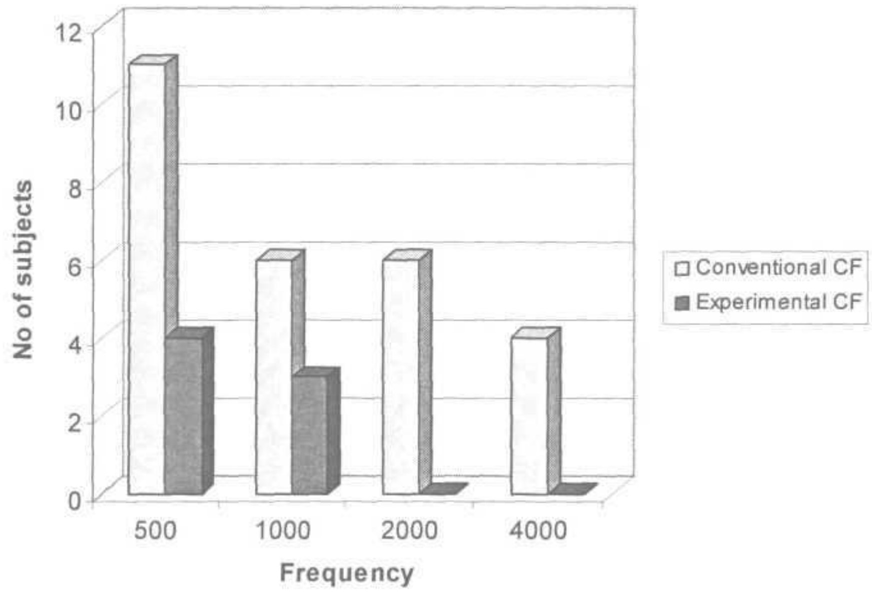

Figure 4: Number of individuals with artifacts for bone conducted stimuli

Table 8: Results of equality of proportions to compare the percentage of subjects with artifacts in conventional and experimental carrier frequencies

Frequencies (Hz)	**Z score**	
	Head phone	**Bone vibrator**
500 & 522	1.92	1.25
1000 & 1022	2.24*	1.28
2000 & 2022	2.99*	2.75*
4000 & 4022	2.16*	2.16*

* Significant at 0.05 level.

Equality of proportions test showed that there was a significant difference ($p < 0.05$) between 1000 & 1022 Hz, 2000 & 2022 Hz, and 4000 & 4022 Hz in terms of percentage of subjects in whom artifacts were present, when ASSR was elicited by air conducted stimuli. When ASSR was elicited by bone conducted stimuli there was a significant difference ($p < 0.05$) between 2000 & 2022 Hz, 4000 & 4022 Hz in terms of percentage of subjects in whom artifacts were observed. There was no statistically significant difference ($p > 0.05$) in percentage of subjects in whom artifacts were present between 500 & 522 Hz for air conduction transducers and between 500 & 522 Hz, 1000 & 1022 Hz for bone conduction transducer.

Upper limit for artifact free ASSR measurements

Table 9 shows the mean and standard deviation of minimum levels at which artifacts occurred across the carrier frequencies for air conducted and bone conducted stimuli and maximum intensity at which artifact free ASSR can be recorded

Table 9; Mean and SD of minimum level at which artifact occurred and the maximum limit for artifact free ASSR measurement in dBHL.

Frequency	Transducer					
	Head phone			Bone vibrator		
	Mean	SD	Max limit	Mean	SD	Max limit
500 Hz	98.57	4.97	85	56.81	3.37	45
522 Hz	106.0	3.94	95	60.0	0.00	55
1000 Hz	109.16	6.33	90	73.33	2.58	65
1022 Hz	112.5	3.94	100	78.33	5.00	70
2000 Hz	108.0	5.37	95	80.83	6.40	65
2022 Hz	110	0.00	105	-	-	85
4000 Hz	112.5	5.00	100	70.00	0.00	65
4022 Hz	-	-	115	-	-	70

It can be observed from the Table 9 that the dynamic range for artifact free ASSR measurement is higher for experimental carrier frequencies when compare to conventional carrier frequencies.

CHAPTER 5

DISCUSSION

In the present study it was found that using the experimental carrier frequency reduces the presence of artifacts. The exact sampling frequency that is used in instrument is not known. However Small and Stapells (2004) reported that commercially available ASSR systems use the A/D to conversion rates of 500 Hz or 1000 Hz as default setting, So it was assumed that this instrument also uses similar A/D rate and the carrier frequencies were changed such a way that they were not integer multiple of 500 Hz or 1000 Hz. Results revealed that using the experimental carrier frequency reduced the occurrence of artifacts. This supports the notion that these artifacts might be due to electro magnetic aliasing effect. The change in carrier frequency may not allow the electromagnetic carrier signal to alias at the modulation frequency if the A/D rates are 500 Hz or 1000 Hz (Picton & John, 2004). Similar results have been reported by other investigators, when they changed the sampling rate (Picton & John 2004; Small & Stapells 2004)

The artifact reduction for stimuli of low frequencies (522 & 1022 Hz) is less when compared to high frequencies (2022 & 4022 Hz). The persistence of artifacts at low frequencies may be attributed to physiological artifacts. The artifacts may be of vestibular origin. Vestibular stimulation is larger at low frequencies when compared to high frequencies (Townsend & Cody, 1971; Todd, Cody & Banks, 2000). Small and Stapells (2004) reported that vestibular evoked myogenic potential from inion muscle could be recorded by an electrode placed on the nape. However in the present study electrodes were placed on mastoids and forehead/vertex. This electrode placement is not suited for picking vestibular evoked myogenic potentials. There are reports of a negative potential N3, generated from the vestibular nuclei through stimulation of saccule (Nong, Ura, & Noda, 2000) which could be picked up by using conventional electrode placements (Fore head/Vertex to mastoid) in profound hearing loss individuals. An investigation by Name, Nambi, and Vanaja, (2006) also supported the possibility of vestibular artifacts while recording ASSR at high intensity based on latency calculations from the phase delay which falls around 3-5 msec. They reported that these physiological artifacts mainly contaminated the ASSR elicited by the 500 Hz carrier signal. However in current study the artifacts persisted for 1022 Hz carrier signal also. Occurrence of artifacts at this frequency may also be of vestibular origin. Vestibular stimulation by 1000 Hz acoustic signal has also been reported in the literature (Cheng, Huang & Young, 2003; Welgampola & Colebatch, 2001)

Another possible reason for obtaining more artifacts at low frequencies are related to the electrical energy required to drive the oscillator. It has been reported that less electrical energy is required to drive the oscillator at high frequencies (2000 Hz & 4000 Hz) when compared to low frequencies (500 Hz & 1000 Hz) (Small & Stapells, 2004). So, the electromagnetic energy that radiated during the generation of high frequency signals will be less when compared to low frequency signal, which in turn might reduce the amplitude of electromagnetic stimulus artifacts. A third reason may be that the higher carrier frequencies will be away from the EEG low pass filter setting and thus stimulus artifact would be smaller in amplitude (Small & Stapells, 2004).

A statistically significant difference was found between the ASSR for stimuli presented through two transducers only at 1000 Hz, but the visual inspection of the data revealed that there was fewer artifacts for bone conducted stimuli when compared to air conducted stimuli. In the current study the forehead bone vibrator placement was used and the electrodes were placed on mastoids and vertex for air conduction testing the electrodes were placed on mastoids and forehead. So the physical proximity between transducer and the electrode was more in case of bone vibrator when compared to head phone. This might have reduced the amplitude of electromagnetic energy reaching the electrode which in turn probably reduced the occurrence of artifacts. Also forehead bonevibrator placement of the bone oscillator might result in less vestibular stimulation, possibly due to the different mode of stimulation compared with temporal bone placement. (Small & Stapells, 2004). In the current study ASSR for air conducted and bone conducted stimuli was not obtained from the same subject due to time constraints. The individual variability among the subjects may also be able to have accounted for the difference in the percentage of subjects in whom artifacts were observed.

According to the current study the upper limit for artifact free ASSR measurement is 85dBHL for headphone and 45dBHL for bonevibrator at 500 Hz. It was higher for high frequencies. Name, Nambi, and Vanaja (2006) also reported that upper limit for artifact free ASSR measurement for head phone is 90 dBHL and for insert ear phone is 105 dBHL is consonance with current study. Study by Gorga et al. (2004) reported that for insert earphone upper limit for artifact free ASSR measurement is 85 dBHL and for bone vibrator it is 40 dBHL (Small & Stapells, 2004). In studies by Gorga et al. (2004) and Small and Stapells (2004) the intensity at which artifacts occurred was lower when compared to that found in the current study and the study by Name, Nambi and Vanaja (2006). This might be due the difference in analysis method used for recording ASSR in the two studies. The earlier studies used weighted averaging method where the averaging of signals are done at modulation frequency and adjacent frequencies then amplitudes are compared. But in current study phase coherence method was used where the phase delays of the responses are being compared. The upper limits for artifact free ASSRs elicited by experimental carrier frequencies were high when compared to ASSRs elicited by conventional carrier frequencies. This may because experimental carrier frequencies reduced the electromagnetic artifacts and mainly contaminated by physiological artifacts. The physiological artifacts might occur at little higher intensities when compared to stimulus artifacts thus the upper limits for artifact free ASSR measurements for experimental carrier frequencies enhanced.

Thus the results of the present study suggest that occurrence of artifacts may be reduced in ASSR by changing the carrier frequencies in such a way that it is not an integer multiple of sampling frequency.

CHAPTER 6

SUMMARY & CONCLUSION

ASSR is one of the physiological tests that developed for threshold estimation. After the invention of ASSR data have begun to accumulate that suggest that ASSR predicts behavioral thresholds accurately and it can differentiate severe to profound hearing loss. But the presence of the artifacts at high intensities limits the usefulness of ASSR in differentiating severe to profound hearing loss (Gorga et al., 2004). These artifacts might be due to electromagnetic aliasing effects (Small & Stapells, 2004; Picton & John, 2004) and/or due to the stimulation of vestibular end organs (Small & Stapells, 2004; Name, Nambi, & Vanaja, 2006). Attempts have been made to avoid the electro magnetic aliasing artifacts in weighted averaging method of response detection. The approaches used include, changing the sampling frequency to whose integer multiples are not carrier frequencies (Small & Stapells, 2004; Picton & John, 2004) and increasing the sampling rate to nyquist frequency (Picton & John, 2004) or using different stimulus such as alternating amplitude modulated tone and beat stimuli (Picton & John, 2004). Another approach which can probably avoid the electromagnetic artifacts is changing the carrier frequency in such a way that they are not integer multiples of sampling frequencies (Picton & John, 2004). Research needs to be done to check whether changing the carrier frequency can avoid the artifacts or enhance the dynamic range of ASSR for artifact free measurements. There is also a need to compare the occurrence of artifacts at different carrier frequencies and across the air conduction and bone conduction transducer.

Hence the current study aimed to investigate the following:

- To determine the upper limits for artifact free ASSR measurements for air conduction and bone conduction transducers for ASSR analyzed using phase coherence method for conventional carrier frequencies.
- To investigate if the artifact can be avoided or dynamic range of ASSR for artifact free measurements be enhanced by using the carrier frequencies which are not integer multiple of sampling frequencies.
- To compare the percentage of individuals in whom artifacts are observed at different carrier frequencies
- To compare the percentage of individuals in whom artifacts are observed for the stimuli presented through headphone and bonevibrator.

ASSR for air conducted and bone conducted stimuli were recorded from 15 participants. Subjects who did not show any behavioral responses to pure tone and modulated tone of conventional (500, 1000, 2000 & 4000 Hz) and experimental carrier frequencies (522, 1022, 2022 & 4022 Hz) at maximum presentation levels were considered for the study. Testing was initiated at the maximum limit of the instrument and the intensity was varied in 5 dB steps to find out the intensity level at which artifact free ASSR measurement can be obtained.

The results of the study revealed that artifacts occurred when the conventional carrier frequencies are used to record the ASSR for both air conducted and bone conducted stimuli. When the experimental carrier frequencies were used, the occurrence of artifacts significantly reduced at higher frequencies but artifacts persisted in some individuals at low frequencies. It was hypothesized that the experimental carrier frequencies probably have reduced electro magnetic aliasing artifacts and the persisted artifacts might be due to physiological artifacts through the vestibular stimulation. The use of experimental carrier frequencies at least enhanced the dynamic range for artifact free ASSR measurements in those frequencies where artifact could not be avoided. As the frequency of the carrier signal increases percentage of individuals in whom artifacts were obtained reduced for both air conducted and bone conducted stimuli. Overall less number of individuals had artifacts when ASSR was recorded through bone conducted stimuli when compared to air conducted stimuli.

Implications

The experimental carrier frequencies can be used while assessing individuals with severe to profound hearing loss. The investigation also throws some light on the generators of artifacts.

Future directions

- Threshold estimation using experimental carrier frequencies can be carried out in individual with hearing loss and in individual with normal hearing to evaluate efficiency of experimental carrier frequencies for threshold estimation.
- Upper limit for obtaining artifact free ASSR need to be determined for stimuli presented through insert ear phone using experimental carrier frequencies.
- ASSR for experimental carrier frequencies can be compared between profound hearing loss individuals and simulator of human head and torso to give more insight about the mechanism of artifacts
- ASSR for conventional and experimental carrier frequencies can be evaluated on individuals with vestibular neurectomy with profound hearing loss to investigate if artifacts are avoided or reduced when there is no vestibular involvement.

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