Compressive Non-linearity of Basilar Membrane-Evaluation through Electrophysiological Test

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Abstract

Outer hair cells have special characteristic called the non-linearity which provides gain to low intensity sounds. In case of sensorineural hearing loss, loss of this property leads to perceptual deficits. This study was carried out to find out if auditory brainstem response (ABR) with a paradigm of forward masking could be used to measure the basilar membrane non-linearity. Wave V of ABR was obtained for normal hearing individuals and those with sensorineural hearing loss, for On-frequency and Off-frequency paradigm of forward masking. Result of this study indicated loss of non-linear function in cases with sensorineural hearing loss.

***Key words**: Forward masking, non-linearity, auditory brainstem response, ABR.*

Cochlea is the most mechanized part of the inner ear structures which help in transduction of the sound energy by converting them into electrical impulse, which would be coded in the neurons, in turn stimulating the auditory area.

The response of the healthy mammalian basilar membrane to sound is sharply tuned, highly non-linear, and compressive. Cochlear hearing loss is associated with an increase in absolute threshold, an abnormally rapid growth in loudness with level, and a loss of frequency selectivity. The effect of abnormal growth of loudness, or ''loudness recruitment'', may be due to a loss of compression in the cochlea (Glasberg & Moore, 1992).

Physiological studies of the basilar membrane (BM) have provided a great deal of information about the nature of the non-linearity, these are restricted to very high and very low characteristic frequency (CFs): only the basal and apical turns of the cochlea are readily accessible.

Psychophysical studies done on humans have also shown similar response behavior using various behavioral measures of cochlear nonlinearity, including 'growth of forward masking' (Oxenham & Plack, 1997), 'temporal masking curves' (Nelson, Schroder, & Wojtczak, 2001) and masking additivity (Plack, Oxenham & Drga, 2006). But the psychophysical tests are vulnerable to subjective variability and uniform results couldn't be obtained. Given the perceptual consequences of sensorineural hearing loss, an objective measure of cochlear compression in humans could have a considerable clinical value (Ananthanarayan & Plack, 2009). Since there are no studies to evaluate the cochlear compression in subjects with cochlear hearing loss this study is planned and carried out.

The aim of the study was to evaluate an electrophysiological test to study the basilar membrane nonlinearity in clients with sensorineural hearing loss using Auditory Brainstem Response.

A fundamental property of the peripheral auditory system is that it operates as a frequency analyzer. When the sound reaches the ear drum, it is transmitted via the vibrations of the middle ear to the oval window. At low sound levels, the frequency that produces the greatest response at a given point along the basilar membrane is known as the characteristic frequency of that point. The cochlea has a special property which helps to enhance the low level sounds and provide little or no gain to the high level sounds thus making the system non-linear in nature.

Psychophysical method such as masking has been used to study the compression property of the cochlea, specifically the Outer Hair Cells. Masking is one such method to calculate the compression of basilar membrane. Simultaneous masking used in several studies gave rise to Suppression phenomenon where it measured linear response. To overcome this Forward masking phenomenon was used, so the stimuli used would not physically overlap (Oxenham & Plack, 1997). This method was called as the Growth of Masking Paradigm, which considered the intensity aspect of the stimulus. This led to Spectral Splatter. To overcome this, Oxenham and Plack used high- pass masking noise.

Another important Paradigm introduced by Nelson, Schroder, and Wojtczak (2001) is called the Temporal Masking Curves (TMCs) which takes into consideration the temporal aspects.

Method

Participants: The participants for the experiment consisted of 2 groups.

The Control group consisted of 15 normal hearing (30 ears) human adult subjects, ranging in

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age from 20-55 years (mean age =30 years), participated in the study.. Hearing sensitivity in all the subjects was better than 15 dB HL (mean PTA =9.6 dB HL) for octave frequencies from 250-8000Hz. The speech discrimination scores were ≥90%. The client had no history of conductive pathology.

The experimental group consisted of 15 adults (30 ears), ranging in age from 20-55 years (mean=48 years), with mild to moderate sensorineural hearing loss were selected as subjects for the study. The hearing sensitivity of all the subjects varied from ≥26 dB HL to ≤55 dB HL (Mean =35.6 dB) for octave frequencies 500 Hz, 1000Hz, and 2000 Hz in both ears. Hearing thresholds at 4000Hz did not exceed 65 dB HL. All the clients had flat or gradual sloping configuration with slope of 5-12 dB/octave (Lloyd & Kaplan, 1978). Speech discrimination scores of the client was ≥70%. All the clients had 'A' type tympanogram with present or elevated reflexes. They had no history of middle ear infection. No history of retro cochlear pathology. Uncomfortable level (UCL) for speech for all the subjects was greater than 105dB.

Stimuli: A tone-on-tone forward masking paradigm was used in this study. Two stimuli were generated, one for On-frequency masking (stimulus 1) and other for Off-frequency masking (stimulus 2). The probe tone had a frequency of 4000Hz with duration of 4ms, including 2ms cosine squared ramps (2-0-2).

The masker consisted of a 4 kHz tone burst (on-frequency masker) or a 1.8 kHz (off frequency masker). The overall duration of the masker was 100 ms including an 80-ms steady state duration as well as 10-ms cosine-squared on-set and off-set ramps. The time interval between the masker off set and the probe onset will be 5ms.

The probe tone intensity is fixed at 60 dBSPL and the masker level is varied from 50 dB SPL to 70 dB SPL in 10 dB steps. The stimulus was generated using personal computer model HP Probook 4410S using Matlab 7.01 software.

Instrumentation: Calibrated diagnostic audiometer Orbiter 922 was used to estimate the pure-tone thresholds and Uncomfortable level for speech for all the subjects. Calibrated middle ear analyzer GSI-Tympstar was used for tympanometry and reflexometry. IHS Smart EP version: 3140 (Intelligent hearing systems, Florida, USA) – was used to record and analyze the responses.

Procedure: Pure tone threshold were obtained using modified version of the Hughson and Westlake procedure (Carhart & Jergser, 1959, cited in Silman & Silverman, 1991) across octave frequencies from 250-8000Hz for air conduction and from 250-4000Hz for bone conduction.

Uncomfortable loudness level of the subjects was determined through headphones TDH-39 at different intensities using ascending method. The Uncomfortable level for speech would be the hearing level at which the subjects considers speech material to be uncomfortably loud. This was done to rule out the presence of recruitment.

Tympanometry and reflex evaluation was carried out using 226 Hz probe-tones to know the status of the middle ear.

Auditory Brainstem Response (ABR) was elicited to rule out the presence of retro-cochlear pathology. The electrode sites namely, forehead and mastoid on both the sides were cleaned with the help of skin preparing gel. Electrodes were then placed on the sites with conduction paste and secured with skin tape. The stimuli and the acquisition parameters used to record ABR are shown in Table 1.

Procedure for recording Auditory Brainstem Response using Tone-on-tone forward masking stimuli: Subjects who fulfilled the selection criteria based on the above mentioned audiological tests underwent ABR with the tone-on-tone forward asking paradigm.

Participants were placed comfortably in a reclining chair. The electrode sites were cleaned with skin preparing gel. The electrodes were cleaned with ethanol before placing on the respective sites. Electrodes were dipped in skin conduction paste, fixed to the scalp and secured with skin tape.

Procedure for recording Auditory Brainstem Response using Tone-on-tone forward masking stimuli: Subjects who fulfilled the selection criteria based on the above mentioned audiological tests underwent ABR with the tone-on-tone forward asking paradigm. Participants were placed comfortably in a reclining chair. The electrode sites were cleaned with skin preparing gel. Electrode montage used to record ABR is given in the Table 2.

Evoked response was recorded differentially between scalp electrodes placed on the midline of the forehead (non-inverting), ipsilateral mastoid (inverting) and contralateral mastoid serving as ground.

Table 1. Stimulus and acquisition parameters for ABR

Stimulus parameters		Acquisition parameters	
Stimulus	Click	Mode	Monaural stimulation
Duration	100μs	Electrode type	Disc electrodes
Stimulus rate	11.1/s and 90.1/s	Electrode montage	Non-inverting: Fpz Inverting: A1/A2 Ground: A2/A1
Polarity	rarefaction	Analysis window	15 ms
		Filter settings	100 Hz-3000Hz
Number of sweeps	1500	Notch filter	on
Intensity	90 dB HL	Impedance	Inter electrode: 2kΩ Intra electrode: 5kΩ
Transducer	ER-3A insert earphones	No. of channels	Single channel

Table 2. Stimulus and acquisition parameters for recording ABR for Forward masking procedure

Stimulus Parameters		Acquisition Parameters	
Stimulus	Tone-on-tone forward masking A.On-frequency masking(4kHz probe tone 4kHz masker) B.Off-frequency masking (4kHz probe tone with 1.8 kHz masker)	Mode	Ipsilateral
		Electrode type	Disc electrode
		Amplification	1,50,000
		Analysis window	20ms
		Filter settings	100Hz-3000Hz
Duration	120ms	Electrode montage	Non-inverting: Fpz Inverting: A1/A2 Ground: A2/A1
Stimulus rate	3.93/s	Notch filter	ON
Polarity	Alternate	Impedance	Inter electrode: within 2kΩ Intra electrode:<5kΩ
Intensity	Probe tone: 60 dBSPL Masker: 50 dBSPL to 70 dBSPL varied in 10dB steps		
		Recording window	25ms
No. of sweeps	1500	Transducer	ER-3A Insert phones

Response evaluation: Acoustically evoked ABR were recorded twice for both the conditions to check for the reliability and stored in the hard drive of the computer. It was later retrieved and the Wave V was marked. The latency at which the Wave V was occurring was noted for both on and off frequency masking conditions. The latencies obtained were subjected to statistical analysis. Mean latency of Wave V was compared between the control and the experimental groups.

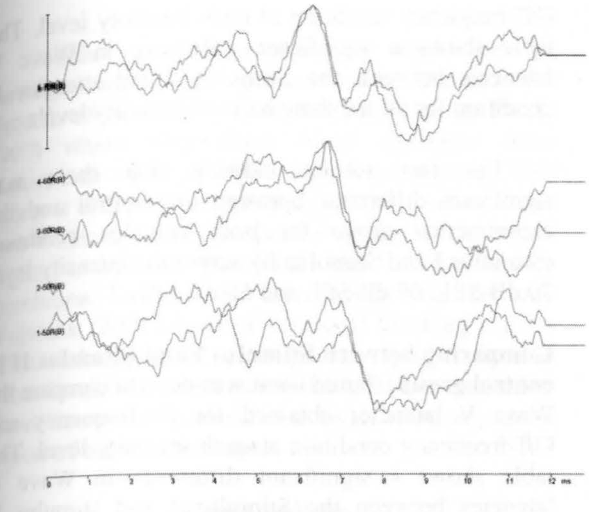

Figure 1. ABR obtained for On-frequency masking condition.

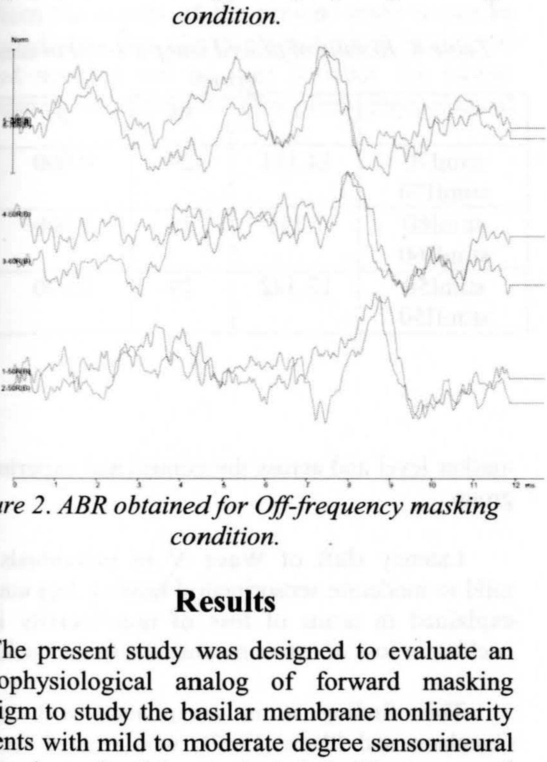

Figure 2. ABR obtained for Off-frequency masking condition.

Results

The present study was designed to evaluate an electrophysiological analog of forward masking paradigm to study the basilar membrane nonlinearity in clients with mild to moderate degree sensorineural hearing loss. Participants included fifteen normal hearing individuals and fifteen individuals with mild to moderate sensorineural hearing loss. ABR was done on all the individuals using tone-on-tone forward masking paradigm and Wave V latencies (ms) obtained.

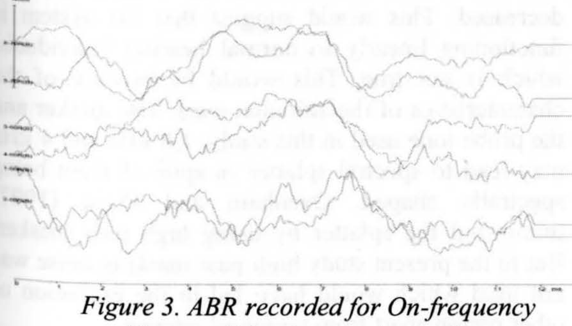

Figure 3. ABR recorded for On-frequency masking condition in experimental group.

The following statistical analysis was done to compare the control and the experimental group. Descriptive statistics was done to obtain mean and standard deviation for wave V latencies of the ABR in control and experimental group. Repeated measure analysis (mixed ANOVA) was done to check for significant difference in latencies of wave V across the groups and across the stimulus level. Bonferroni's post hoc test was administered to analyze if the wave V latency differed with different levels of intensity. Independent sample t-test was administered on the data to check for significant difference between the groups on wave V latencies. Wave V latencies obtained from On- frequency masking (stimulus I) and Off-frequency (stimulus II) were compared separately for control and experimental group using Paired sample t-test.
Characteristics of latency change for on-versus off-frequency Masking

The ABR waveforms, for On-frequency and Off-frequency stimulus condition are shown in figure 1 and 2. There is a progressive shift in wave V latency with the decrease in intensity of masker, and the shift is more for off-frequency masker condition.

Characteristics of ABR waveforms in control group: As seen in Figure 1 and 2, there was a shift in latency of the wave V with the decrease in intensity for the control group. Wave V was present in all the participants.

Characteristics of ABR in experimental group: Figure 3 and 4 are the recordings of the waveform obtained from individuals with sensorineural hearing loss. Shift in latency with decrease in intensity was observed in experimental group. Shift in Wave V latency was more for off-frequency masking condition than for on-frequency masking condition.

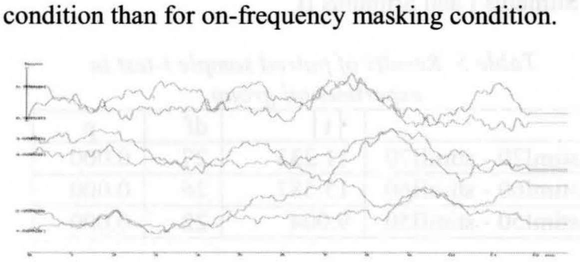

Figure 4. ABR recorded for Off-frequency masking condition in experimental group.

Comparing the Wave V latencies in control and experimental group: Mean and standard deviation for Wave V (msec) for control and experimental group, for both on-frequency (Stim I) and off-frequency (Stim II) condition were obtained.

Mixed analysis of variance was carried out to compare between the groups on latencies obtained for On-frequency and Off-frequency stimulus condition at three intensity levels. The results indicate that the Wave V latency was significantly different between the groups [F (1, 51=96.46, p=0.000]. Independent sample t-test was done to know if significant difference existed between the stimulus intensity for On-frequency and off-frequency stimulus. The test results indicate that there was significant difference between the control and the experimental group for both stimulus condition (Stimulus I and Stimulus II) across the intensity level 70 dB SPL, 60 dB SPL and 50 dB SPL.

Table 3. Results of independent sample t test

	t	df	p
stimI70	11.007	56	0.000
	11.131	52.67	0.000
stimI60	7.794	55	0.000
	7.834	54.99	0.000
stimI50	9.985	55	0.000
	9.976	54.15	0.000
stimII70	7.649	56	0.000
	7.657	55.91	0.000
stimII60	8.694	56	0.000
	8.636	52.54	0.000
stimII50	7.684	51	0.000
	8.024	50.81	0.000

Comparing between Stimulus I and Stimulus II in control group: Paired t-test was done to compare the Wave V latencies obtained for On-frequency and

Comparing between Stimulus I and Stimulus II in experimental group: Paired sample t-test was administered on experimental group to check for significant difference between the Stimulus I and Stimulus II condition across the three masker levels. The results indicated significant difference between Stimulus I and Stimulus II.

Table 5. Results of paired sample t-test in experimental group.

	t	df	p
stimI70 - stimII70	11.233	27	0.000
stimI60 - stimII60	13.587	26	0.000
stimI50 - stimII50	9.004	22	0.000

Discussion

The aim of the study was to evaluate an electrophysiological analog of forward masking paradigm to study the basilar membrane nonlinearity.

Latencies of wave V as an indication of non-linear function of basilar membrane: Latencies of wave V obtained for three masker conditions, for On and Off-frequency masking paradigm were evaluated and it was found to have significant difference between

Off-frequency condition at each intensity level. The table shows a significant difference in Wave V latencies between the Stimulus I and stimulus II condition for all the three pairs of intensity levels.

The test results indicate that there was significant difference between the control and the experimental group for both stimulus condition (Stimulus I and Stimulus II) across the intensity level 70 dB SPL, 60 dB SPL and 50 dB SPL.

Comparing between Stimulus I and Stimulus II in control group: Paired t-test was done to compare the Wave V latencies obtained for On-frequency and Off-frequency condition at each intensity level. The table shows a significant difference in Wave V latencies between the Stimulus I and stimulus II condition for all the three pairs of intensity levels.

Table 4. Results of paired sample t-test in control group

	t	df	p
stimI70 stimII70	14.111	29	0.000
stimI60 stimII60	7.791	29	0.000
stimI50 stimII50	13.342	29	0.000

masker level and across the control and experimental group.

Latency shift of Wave V in individuals with mild to moderate sensorineural hearing loss could be explained in terms of loss of non-linearity in the cochlea or loss of active mechanism in the cochlea.

This finding is in accordance with studies Oxenham and Plack (1997), who studied the non-linearity in the cochlea and concluded that subjects with cochlear hearing loss, have linear slopes suggesting loss of compressive mechanism.

Latencies of Wave V obtained in normal hearing individuals also increased as the masker intensity decreased. This would suggest that the system is functioning linearly in normal hearing individuals, which is not true. This would be because of the characteristics of the stimulus used. The masker and the probe tone used in this study, 1.8 kHz and 4 kHz may lead to spectral splatter in spite of them being spectrally shaped. Oxenham and Plack (1997) minimized the splatter by using high pass masker. But in the present study high pass masking noise was not used which would have led to the excitation of other region apart from region of interest.

Another possible explanation would be the paradigm used. The present study utilized the Growth of Masking paradigm (Oxenham & Plack, 1997) where very short signal durations were required in order to mask high-level signals. This makes it difficult to employ signal frequencies lower than 4 kHz because the spectral spread of the signal begins to exceed the bandwidth of the basilar membrane. To overcome this Nelson, Schroder, and Wojtczak (2001) devised Temporal Masking Curves (TMCs). In the TMC technique the signal is fixed at a low level, and hence presumably causes excitation above detection threshold over fixed, relatively small region of basilar membrane.

Conclusions

From the results of the present study it can be concluded that the electrophysiological analog of forward masking can be used to study the basilar membrane characteristics. This electrophysiological analog can be used instead of psychophysical measures in difficult to test population.

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