Distortion product otoacoustic emissions: comparison of sequential vs. simultaneous presentation of primary tones

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Abstract Distortion product otoacoustic emissions are one form of evoked otoacoustic emissions. DPOAEs provide the frequency specific information about the hearing status in mid and high frequency regions. But in most screening protocols TEOAEs are preferred as it requires less time compared to DPOAE. This is because, in DPOAE each stimulus is presented one after the other and responses are analyzed. Grason and Stadler Incorporation 60 (GSI-60) offer simultaneous presentation of four sets of primary tones at a time and checks for the DPOAE. In this mode of presentation, all the pairs are presented at a time and following that response is extracted separately whereas, in sequential mode primaries are presented in orderly fashion one after the other. In this article simultaneous and sequential protocols were used to compare the Distortion product otoacoustic emission amplitude, noise floor and administration time in individuals with normal hearing and mild sensori-neural (SN) hearing loss. In simultaneous protocols four sets of primary tones (i.e. 8 tones) were presented together whereas, in sequential presentation mode one set of primary tones was presented each time. Simultaneous protocol was completed in less than half the time required for the completion of sequential protocol. Two techniques yielded similar results at frequencies above 1000 Hz only in normal hearing group. In SN hearing loss group simultaneous presentation yielded significantly higher noise floors and distortion product amplitudes. This result challenges the use of simultaneous presentation technique in neonatal

hearing screening programmes and on other pathologies. This discrepancy between two protocols may be due to some changes in biomechanical process in the cochlear and/or due to higher distortion/noise produced by the system during the simultaneous presentation mode.

Keywords Otoacoustic emissions · Simultaneous presentation · Sequential presentation · SN hearing loss

Introduction

Hearing impairment is an invisible disability and it is estimated that there are around 24,000 hearing impaired individuals born every year in USA and at least 1 out of 750 in India. Early identification and intervention for hearing impaired child is very crucial as human baby appears to be born with “preexistent knowledge” of language which is further stimulated by auditory mode and help in emergence of language. This development takes place primarily during first three years of life and therefore, it is necessary to have normal functioning of auditory system during this period. Hence, it is emphasized that hearing impairment should be identified soon after birth using sensitive screening techniques.

Any screening tool that is used to measure the auditory sensitivity should be sensitive, comfortable to subjects, fast and reliable. Otoacoustic emissions (OAEs) fulfill many of these criteria and hence, have become an indispensable tool in screening infants for hearing loss. Distortion product otoacoustic emissions (DPOAEs), which are one form of evoked OAEs, are elicited by simultaneous presentation of two pure tones which are close by in frequency. They are thought to generate from outer hair cells reflecting non-linear distortion. Most frequently measured DPOAE is intermodulation distortion product i.e. $2f_1-f_2$, as it is the largest measurable DPOAE in human ear [1] (Lonsbury – Martin and Martin, 1990).

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DPOAEs provide the frequency specific information about the hearing status in mid and high frequency regions. But in most screening protocols TEOAEs are preferred as it requires less time compared to DPOAE. This is because, in DPOAE each stimulus is presented one after the other and responses are analyzed. Grason and Stadler Incorporation 60 (GSI-60) offer simultaneous presentation of four sets of primary tones at a time and checks for the DPOAE. In this mode of presentation, all the pairs are presented at a time and following that response is extracted separately whereas, in sequential mode primaries are presented in orderly fashion one after the other.

Beattie [2] compared the noise floor and distortion product amplitude with these two modes of stimulus presentation. The results suggested that there is no significant difference between DPOAEs obtained in two modes. Simultaneous presentation would be of great use in neonatal screening programmes if efficiency of this technique is equivalent to that of sequential presentation mode even in hearing impaired individuals.

Hence, there is a need to compare DPOAEs obtained using these two presentation modes in hearing impaired individuals to validate the simultaneous presentation mode. Present study aimed at comparing the distortion product (DPs) amplitudes, noise floors (NFs), and administration time using simultaneous and sequential presentation modes in normal hearing and mild sensori-neural (SN) hearing loss group.

Methods

Subjects

35 individuals divided into two groups, participated in the study. Group I consisted of 15 individuals with mild SN hearing loss in the age range of 18 to 60 years, with the mean age of 39 years. Group II consisted of 20 individuals with normal hearing sensitivity. Both the groups were matched for age and gender. Selection of the ear was done randomly.

All the subjects underwent routine pure tone audiometry, speech audiometry and immittance evaluation. All the tests were done using calibrated instruments in a sound treated room. For group I mean pure tone average was 35.5 dB HL (range: 20 dB HL – 45 dB HL) and all had Jerger 'A' type tympanogram with acoustic reflexes present in the ear tested. All the subjects in group II had hearing thresholds within 15 dB HL at octave frequencies between 250 Hz to 8000 Hz. All of them had normal tympanogram and acoustic reflexes present within normal limits. None of the thirty five subjects had any history of middle ear pathologies or any neurological abnormalities.

Instrumentation

All the testing was carried with commercially available system for DPOAEs, using Grason Stadler-60 (GSI-60),

application Software version 4.7. In the probe assembly of GSI-60, there are three probes, two for the presentation of primaries and one for the microphone which is connected to computer further. Sampling rate was 16 Hz in series of 32 ms segments (frames). Then a Fast Fourier Transform was done which yielded a total of 512 bin data, with each bin of 31.25 Hz width.

Test stimuli

Eight pairs of frequencies in which f_2 was at 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 2500 Hz, 4000 Hz and 4500 Hz were presented at an $f_2:f_1$ ratio of 1.20 [3]. In this article data is represented with reference to f_2 . Intensities of the primary tones were maintained at 75 dB SPL (L1) and 65 dB SPL (L2). L2 was 10 dB more than the L1 as it results in good DPOAE values [3,4,5]. In the simultaneous presentation mode 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz were presented together followed by 750 Hz, 1500 Hz, 2500 Hz and 4500 Hz.

Data acquisition criteria

Testing at a given frequency was terminated when a signal to noise ratio of 10 dB was attained. However a minimum of 100 frames and maximum of 500 frames were averaged. Moreover, a frame was rejected if it exceeded the 30dB SPL rejection criterion or if L1 and L2 differed by more than 2 dB from the target values. These test acceptance criteria and test rejection criteria were selected because they are consistent with the values that are employed in clinical settings with this instrumentation [6–9].

Noise floor measurements

The root mean squared (RMS) noise calculation averaged two bins of data (62.5Hz) on either side of the DPOAE bin. For each sweep, the average noise value from these four bins was compared to the rejection criterion (30 dB SPL) for either acceptance or rejection of the sweep. If the noise level in the four bins was less than 30dB SPL, the sweep was accepted and the complex Fast Fourier Transformed values were averaged in an accumulator. The noise floor levels were computed from two bins on either side of the $2f_1-f_2$ frequency for the sequential protocol, where f_2 is 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 2500 Hz, 4000 Hz and 4500 Hz. For the simultaneous protocol, the GSI system uses the noise floor corresponding to the first set of primary-tone pairs per group when applying the data acquisition criteria for frame rejection, test rejection and test acceptance. Because the frequency pairs were always presented from low to high frequency for the simultaneous protocol, the noise floor was measured around $2f_1-f_2$ where f_1 was 416 Hz and f_2 was 500 Hz.

Procedure

The instrument GSI-60 DPOAE analyzer allows selecting simultaneous and sequential modes under the “Custom DP Stimulus” menu. Subjects were seated in a comfortable position and were instructed to be quiet and still. Subjects were seated away from the computer to minimize the noise floor (noise from computer). Subjects were tested in two stimulus presentation modalities without altering the positioning of the probe. The order of the testing was counterbalanced to avoid any order effect.

Results

This investigation aimed at comparison of DPOAEs, obtained using simultaneous presentation of 8 primary tone pairs to that of sequential presentation in normal hearing individuals and individuals with mild SN hearing loss.

Table 1 shows the mean and Standard deviation (SD) of DP amplitudes and NFs obtained in these two pro-

ocols on normal hearing subjects. Simultaneous mode resulted in higher DP amplitudes and noise floor levels at all the frequencies tested. One way ANOVA revealed a significant difference ($p < 0.05$) in DP amplitudes between sequential and simultaneous protocols at 500 Hz, 750 Hz and 1000 Hz. The simultaneous protocols produced significantly higher noise floors ($p > 0.05$) than sequential protocol at the same frequencies and also at 2500 Hz.

Table 2 shows the mean and SD values of DP amplitudes and NFs for the two protocols in SN hearing loss group. One way ANOVA revealed a significant difference in DPOAE amplitudes between two protocols at 500 Hz, 750 Hz, 1000 Hz, 1500 Hz, 2000 Hz, 2500 Hz and 4000 Hz. NFs in the simultaneous protocol was significantly higher ($p < 0.05$) at 750 Hz, 1000 Hz, 1500 Hz, 2500 Hz, 4000 Hz and 4500 Hz.

Number of individuals passed in each of the groups with two protocols was calculated taking 6 dB signal to noise ratio (SNR) criteria [10]. Table 3 shows number of normal hearing and SN hearing loss individuals passing

Table 1 Mean and SD values for two protocols in normals

Frequency tested (Hz)	Sequential		Simultaneous	
	DP	NF	DP	NF
500	0.6(6.9)	-7.2(5.4)	10.5(5.2)	-3.1(6.3)
750	1.9(6.1)	-10.6(4.3)	8.3(9)	16.85(5.9)
1000	6.4(4.4)	-10.4(6.8)	11.25(5.10)	2.2(4.9)
1500	10.6(8.4)	-9.3(10.02)	8.6(7.2)	-7.3(7.2)
2000	8.1(6.2)	-15.8(5.6)	4.1(7.7)	15.5(16.3)
2500	6.3(5.4)	-17.6(2.9)	3.8(8.0)	8.4(4.1)
4000	6.5(7.7)	-16.8(3.7)	11.5(4.8)	-15.4(7.8)
4500	0.8(13)	-13.4(5.2)	-0.8(11.4)	5.4(1.6)

Values in parentheses indicate standard deviation

DP = Distortion product amplitude (in dB SPL)

NF = Noise floor (in dB SPL)

Table 2 Mean and SD values for two protocols in hearing impaired

Frequency tested (Hz)	Sequential		Simultaneous	
	DP	NF	DP	NF
500	-5(6.4)	-6.6(3.3)	8.3(5.2)	-6.2(2.8)
750	-3.1(5.8)	-7.9(8.8)	-.05(0.1)	9.2(14.2)
1000	-3.2(12.4)	-13(3.4)	4.1(6.5)	-7.7(10.3)
1500	-4.6(9.2)	-16.0(3.3)	1.4(5.5)	-9.3(13.2)
2000	-9.21(10)	-17.7(3.3)	1.14(4.5)	-17.7(3.5)
2500	-8.5(7.3)	-18.21(3.1)	-2.5(6.6)	7.78(10.9)
4000	-15.9(9.7)	-21.3(3.4)	7.14(7.53)	-14.4(10.1)
4500	-14.6(8.4)	-14.6(2.7)	-15.7(8.1)	4.0(4.4)

Values in parentheses indicate standard deviation

DP = Distortion product amplitude (in dB SPL)

NF = Noise floor (in dB SPL)

the DPOAE test for each of the protocols tested. As it can be seen from Table 3 that, number of individuals passed testing in both the protocols were similar at 1000 Hz, 1500 Hz, 2000 Hz and 4000 Hz in normal hearing group. In SN hearing loss group simultaneous protocols yielded higher or lower pass rate than sequential protocol depending on the frequencies.

Pearson's product moment correlation analysis was performed between SNRs obtained using two protocols in both the groups separately. Table 4 shows "r" and "p" values. From the table it is clear that in normal hearing individuals there was a significant positive correlation between two protocols only at higher frequencies. This was supported also by the results of ANOVA, which showed no significant difference between two protocols at these frequencies. In the SN hearing loss group significant positive correlation was obtained only at 1000 Hz and 4000 Hz. As the same trend was not observed in ANOVA, scatter plots were drawn between SNRs obtained using these two protocols. Figures 1 and 2 shows the scatter plots between two protocols tested, at 1000 Hz and 4000 Hz respectively. From Figs. 1 and 2 it is clear that there was no relation between SNR obtained using these two protocols. The observed positive correlation may be due to some outliers.

Administration time

When primaries were presented sequentially mean administration time was 37 seconds and 160 seconds whereas, in simultaneous presentation mode it was 25 seconds and 51 seconds in normal and hearing impaired group respectively. This difference was statistically significant at 0.001 levels in both the groups. Simultaneous protocol was completed in less than half the time of sequential protocol.

Discussion

In normal hearing group simultaneous presentation protocol yielded significantly higher DP amplitudes and NFs, at frequencies below 1000 Hz whereas, in SN hearing loss group simultaneous presentation mode yielded high DP amplitudes and NFs at most of the frequencies tested. This resulted in condition where many people in hearing loss group failed DPOAE testing (using 6 dB criteria) in sequential and passed in simultaneous mode or vice versa.

When an additional stimulus is applied to the ear, cochlear nonlinear biomechanical process changes. This will result in suppression or enhancement of $2f_1$ - f_2 DPOAE, when an additional pair of stimulus was simultaneously presented [11, 12]. Therefore, simultaneous application of

Table 3 Number of people passed in two protocols normal hearing and SN hearing loss group

Frequency tested (Hz)	Sequential		Simultaneous	
	Normals	SN Hearing Loss	Normals	SN Hearing Loss
500	13	4	16	13
750	14	5	1	1
1000	19	10	18	12
1500	18	9	19	1
2000	19	9	19	13
2500	20	7	0	1
4000	20	6	20	12
4500	17	4	3	2

SN = Sensori-neural

Table 4 Correlation between two protocols in normal and SN hearing loss group

Frequency tested (Hz)	Normals		Hearing impaired	
	r	p	r	p
500	-0.68	0.77	0.24	0.408
750	-0.026	0.93	-0.007	0.98
1000	0.21	0.37	0.57	0.033
1500	0.46	0.03	-0.40	0.154
2000	0.48	0.03	-0.06	0.8
2500	0.40	0.07	-0.16	0.5
4000	0.49	0.02	-0.662	0.01
4500	0.82	0.00	0.65	0.01

Fig. 1 Scatter plot between SNRs two protocols

Fig. 2 Scatter plot of SNR at 4 KHz at 1 KHz

multiple tone pairs is generally expected to produce complex interactions within primaries and in DPs. The present data suggest that these interactions were less in normal hearing group in whom there was no significant difference between two protocols at least at frequencies 1500 Hz and above. Schairer, Clukey, Gould [13] and Beattie [2] have reported that noise level tended to increase with increases in frequency for both simultaneous and sequential conditions. However, they observed that DPOAE levels and noise levels were comparable two conditions, although there were some differences among frequencies. These differences may be due to differences in the probe assembly and/or test environment. But in hearing impaired group, simultaneous presentation yielded high amplitude DPs which were results of complex interaction between primaries and DPs when multiple tones were presented simultaneously.

Another explanation for increased DP amplitudes and NFs in simultaneous presentation mode is increase in sys-

tem distortion and/or system noise because of presentation of 8 tone pairs (4 set of 2 tones). That is, simultaneous presentation of stimuli generated harmonic and/or intermodulation distortions in system which fell in NF and/or DP bins. Each of the bins is 32.25 Hz wide and NF represents the RMS average of two bins (64.5 Hz) on either side of $2f_1-f_2$ frequency bin. If system noise/distortion falls in any of these bins the overall RMS NF values will be elevated. Beattie [2] measured the DP and NFs for the simultaneous and sequential protocol when probe tip was sealed in 2 cc coupler. Simultaneous protocols yielded higher NFs than the sequential protocols when the intensities of primaries were high. DPOAEs represent both DPs and noise (biological, environmental and system) within 31.25 Hz wide bin of interest [14] Larger DPOAE, observed in simultaneous mode, may also reflect system distortions described above.

The correlation analysis and scatter plots illustrate that simultaneous presentation mode cannot be used to measure the DPOAEs, in hearing impaired group. Even though this protocol takes significantly less time than the sequential presentation it overestimated the DP amplitudes and NFs. This may result in erroneous clinical decisions when OAEs are used in neonatal screening programmes.

Conclusion

Even though simultaneous protocol took less time than the sequential protocol, it overestimated the DP amplitude and NFs. As a result many individuals who failed sequential testing, passed in simultaneous mode in hearing impaired group. Hence, this technique may lead to erroneous results if it is used in neonatal screening and/or on cochlear pathologies.

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