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RESEARCH ARTICLE

Threshold of octave masking as a tool to explain cochlear nonlinearity

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Abstract

Background and Aim: The threshold of octave masking test has been used to assess the growth rate of aural harmonics, the intercept point helped differentiate between normal-hearing individuals and sensorineural hearing loss due to noise exposure. With fewer literatures that have been documented, there is a need to explore this test procedure, and hence the purpose of this research is to evaluate the utility of the threshold of octave masking (TOM) procedure in understanding the frequency selectivity and non-linear function of cochlea.

Methods: A total of 10 adults (20 ears) were considered for the test. The TOM test procedure was performed on the subjects where the subjects had to identify the presence of a maskee tone (1 kHz) in the presence of a masker tone (500 Hz) across 5 dB increment of masker tone until the subjects uncomfortable level. A line graph was drawn, extrapolated to identify the point of intercept, which is the threshold of octave masking.

Results: Results reveal that 17 ears did not have a linear growth but had a 10 to 20 dB gap after a particular maskee level. The intercept point of the initial two extreme points was relatively more than the intercept point of the extreme points at higher intensities.

Conclusion: Results from the present study have thrown light on the fact that TOM can be used as a test to measure the frequency selectivity along with the tests of psychophysical tuning curves, notched noise method, non-simultaneous masking, and other non-peripheral masking phenomena.

Keywords: Threshold of octave masking; active mechanism; passive mechanism; nonlinearity; frequency selectivity; psychophysical tuning curves

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Introduction

In the auditory system, the outer hair cells have a unique feature of somatic electromotility by undergoing a periodic change in length related to the sound wave that elicits a membrane potential within the auditory system. They shorten on depolarization and elongate on hyperpolarization [1]. As an objective tool to measure this outer hair cell functioning, the otoacoustic emissions (OAEs) can be used as a reliable tool. The change in the length of outer hair cells generates an acoustic signal through reverse transduction mode [2]. However, there will be a hindrance in

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assessing the outer hair cell (OHC) function in middle ear pathology cases. There will be an absent OAEs as the middle ear cannot perform the reverse transduction process due to middle ear pathology [3].

To overcome this, subjective tests must be equally carried out to assess the OHC functioning. It is the OHC that performs the cochlear amplifier's role and maintains the cochlear nonlinearity [4]. The psychophysical tuning curves (PTCs) are a current method to assess cochlear nonlinearity. In this method, the masker is being attempted to mask the same ear's pure tone at various frequencies. The masker is a wideband noise with a center frequency of desired interest used to mask different pure tone frequencies using a two-interval forced choice method [5]. In normal-hearing individuals, the PTC curves are more sharp and narrow compared to hearing loss individuals where the PTCs curves are broad [6]. Before that, the measurement of best beats and threshold of octave masking (TOM) was incorporated as methods to assess cochlea's aural overload [7]. Normal-hearing individuals perceive the aural overload (aural harmonics) with better sensitivity when made to identify the beats due to the nonlinear distortion in the cochlea by the outer hair cells [8]. However, in individuals with a history of noise exposure, there is an impairment in nonlinear distortion physiology, thus making it difficult for them to perceive beats [9].

The TOM test is a tone on tone masking procedure proposed by Clack and Bess (1969), where the rationale of the test was to measure the threshold and growth rate of aural harmonics. The harmonic threshold and the masking threshold are measured in this test [10]. The test includes a fundamental masker (M_r) and a maskee (M_e), the masker is a tone that is one octave below the maskee, eg masker can be 1000 Hz tone with a maskee frequency of 2000 Hz and the intensity level first needed to cause a shift in the maskee (at least 10 dB SL) was referred to as the TOM [10,11]. The authors have used a Bekesy automated audiometry while administering the test procedure with a double channel audiometer that can generate a phase-locked tonal signal and a tonal masker with a phase shifter feature [11,12]. With a two-interval force choice method used in the psychophysical tuning curves experiment [5], Nelson and Bilger felt the usage of a four interval forced-choice method to give accurate results [12].

The TOM test has been used a clinical utility tool to identify the difference in intensity level required to cause a shift in maskee between normal-hearing individuals and sensorineural hearing loss individuals. It was found out that the intensity level needed to drive a threshold shift was more in normal-hearing individuals than in individuals with sensorineural hearing loss, which explains the fine-tuning of cochlea because of normal OHC functioning in normal-hearing individuals. The point of intercept is low for sensorineural hearing loss individuals than normal-hearing individuals [10-12]. The TOM test has also been used as a predictor to identify temporary threshold shifts (TTS) in noise-induced hearing loss. It was found out that individuals who had a history of noise exposure and who had temporary threshold shifts had a lower TOM when compared to normal-hearing individuals [13,14]. However, Chermak et al. also state that apart from the TOM being less in individuals with noise-induced hearing loss, there is yet clarity needed to understand the relationship between noise-induced hearing loss and TOM thresholds [13]. The TOM is not being used widely in current day to day clinical practice with more usage of psychophysical tuning curves [6].

With a better understanding of TOM procedures and outer hair cells' function, the purpose of this research is to evaluate the utility of the TOM procedure in understanding the non-linear function and the frequency selectivity of the cochlea.

Methods

Before initiating this cross-sectional study, due approval was obtained from the MERF institute of speech and hearing (P) Ltd ethical committee and board for research. The study was taken as a part of the diagnostics process, and informed consent was taken from the subjects.

Participants

The study included a total of 10 adult participants

(20 ears) who were normal-hearing individuals aged between 17 and 21 years with a mean age of 19.6 years and a standard deviation of 1.8. The presence of hearing loss and middle ear pathologies were considered as exclusion criteria.

Instruments used

Immittance audiometry was done using Inventis clarinet middle ear analyzer (Inventis, Padova Italy) with aTDH headphones. Hearing thresholds and threshold of octave masking procedure were carried out using the Inventis piano Clinical Audiometer (Inventis, Padova Italy). A TDH 39 supra-aural headphone was used. A pretest calibration in the audiometer was carried out before the experiment.

Test procedure

Before doing the actual TOM test, all participants underwent an otoscopic examination to check if free of any debris and an immitance audiometry was done where the acoustic immittance and reflexometry were carried out. All participants had an A-type tympanogram and normal acoustic reflex thresholds from 90 to 100 dB at 500 Hz, 1 kHz, 2 kHz, and 4 kHz. PTA was carried out, and a PTA average threshold value less than 15 dB HL in the frequencies 500 Hz, 1 kHz, and 2 kHz was considered a normal-hearing. The most comfortable level (MCL) and uncomfortable level (UCL) were documented too. All subjects had an MCL ranging from 55 to 70 dB, ten ears had a UCL above 100 dB, nine ears had a UCL at 100 dB, and only one ear had a UCL at 95 dB.

The TOM test was carried out by a dual channel audiometer. The test was done ear specific with a masker tone (M_r) and a maskee tone (M_e) provided in the same ear. In our experiment, the frequency of M_e was 1000 Hz pure tone, and M_r was one octave below, a 500 Hz pure tone. The M_r would be continuously presented, and M_e would be given intermittently. The subjects were instructed to identify the M_e tone in the presence of M_r tone. The level of M_r was gradually increased until the subject reported the inaudibility of M_e, later M_r's level was increased in 5 dB steps. A minimum of 10 dB SL shift in M_e should be present from the baseline to note M_r's level that caused this shift [11]. From then onwards, M_r's level will be increased in 5 dB steps until the subject's uncomfortable level. This procedure is repeated for the other ear too. The level of M_r vs. M_e is plotted as a line graph, and based on the first three increment levels, the graph is extrapolated, and the point of intercept is established, which is the TOM (level at which masking first began).

Results

A total of 10 samples (20 ears) were collected, out of which all the samples collected were normal-hearing individuals. The mean age range of the participants was 19.6 years (Table 1).

The level of M_e for a given M_r at various masker intensities is shown in Table 2 for all 20 ears. The initial level of M_r varied from 5 to 10 dB SL amongst subjects (Table 2). The M_r intensity was increased 5 dB steps from its initial value until the subjects uncomfortable loudness level. Out of the 20 ears taken, only three ears had a linear growth in the level of M_e to M_r. The rest 17 ears did not have linear growth, but instead had a gap of 10 to 20 dB HL after a particular level of M_r. It was found out that at an intensity between 50 and 60 dB HL the drastic shift in intensity from a linear growth was seen. Fig. 1 displays the overall slope of a random subject from the threshold of octave masking until high intensities, where it displays a non-linear slope after 50 to 60 dB HL which reveals a possible transition from active phase to passive phase within the cochlea (Fig. 1). The threshold shift for the given M_r was plotted on two separate graphs, as shown in Fig. 2. From the two extreme points, a straight line was drawn and extrapolated to intercept with the abscissa. A graph which had a growth curve until 55 dB of M_r value was plotted separately and a graph with a first point after the slope shift was plotted separately.

Both the graphs were extrapolated as a continued regression line, and the intercept point were noted. The intercept point was considered as the TOM value, and it was found out that the graphical line with a low intensity values had a high intercept point than the graphical line with high

Table 1. Absolute thresholds of 10 subjects (20 ears) at frequencies 500 Hz, 1 kHz and 2 kHz

		Absolute threshold (dB HL)		
Subject	**Ear**	**500 Hz**	**1 kHz**	**2 kHz**
Sub. 1				
	Right	15	10	15
	Left	10	10	10
Sub. 2				
	Right	15	15	10
	Left	10	15	15
Sub. 3				
	Right	10	10	5
	Left	15	15	10
Sub. 4				
	Right	0	0	5
	Left	5	5	0
Sub. 5				
	Right	10	15	15
	Left	10	10	10
Sub. 6				
	Right	5	0	5
	Left	5	5	0
Sub. 7				
	Right	15	15	10
	Left	10	10	5
Sub. 8				
	Right	5	0	0
	Left	10	5	10
Sub. 9				
	Right	10	10	0
	Left	10	10	10
Sub. 10				
	Right	10	15	10
	Left	15	15	15

intensities. The presence of a slope shift across intensities and difference in intercept points can be due to the active and passive mechanisms in cochlea.

Discussion

The slope of the M_e vs M_r were plotted and displayed a growth function curve which indicates the presence of non linearity at a particular point (Fig. 1). The authors call the transition point as the shifting phase from an active cochlea to a passive cochlea. The slope prior to the shift and the slope after the shift were plotted separately and extrapolated to find the intercept point (Fig. 2). The active process of the cochlea is based on the cochlear amplifier by the outer hair cells where they tend to amplify soft sounds until 60 dB, indirectly activating the inner hair cells. On the hand, the passive cochlea is where the inner hair cells get directly activated at 40 dB SL as it comes in contact with the tectorial membrane at that intensity. Cochlea's active mechanism and the presence of outer hair cells enable better fine-tuning and hence improve frequency selectivity as the active mechanism of cochlea acts as a high Q acoustic resonator [15].

The results of this study have shown that the TOM, apart from being used as a tool to predict noise induced hearing loss and a tool used to differentiate sensorineural hearing loss and normal-hearing, it can also be used to comment on the active and passive mechanism in the inner ear [12-14].

For all 20 ears, the initial three points intercepted were relatively higher threshold, which was supported by Grimm and Bess [11], where they stated that the intercept point in normal-hearing individuals was relatively high. Nelson and Bilger [12], in their experiment, found out that in individuals with sensorineural hearing loss, the intercept point or TOM values were relatively lower when compared to the TOM values of normal-hearing individuals.

In this experiment, unlike other TOM experiments, we performed at higher intensities until the subject's uncomfortable level. A linear increase in M_r was seen until a particular intensity after which a gap of 10 to 20 dB HL was seen in most of the subjects (17 ears). The extrapolation was done on two separate graphs. One graph represents a linear growth of M_r from the initial point, and the other graph represents a shift in M_r after a particular M_e intensity. The intercept point obtained for the shift in M_r (at high intensities) was very low, which is similar

Table 2. Absolute threshold of octave masking values and level of maskee (M_e) at different masker (M_r) intensities with the frequency of masker at 500 Hz and maskee at 1 kHz

Sub. 1														
Right ear														
Masker (dB HL)	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**100**			
Maskee (dB HL)	**20**	**30**	**40**	**50**	**60**	**65**	**70**	**75**	**80**	**85**	**85**			
Left ear														
Masker (dB HL)	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	
Maskee (dB HL)	**20**	**25**	**30**	**45**	**50**	**55**	**60**	**65**	**75**	**80**	**85**	**85**	**85**	
Sub. 2														
Right ear														
Masker (dB HL)	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**			
Maskee (dB HL)	**25**	**30**	**35**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**			
Left ear														
Masker (dB HL)	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**			
Maskee (dB HL)	**25**	**30**	**35**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**80**			
Sub. 3														
Right ear														
Masker (dB HL)	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**				
Maskee (dB HL)	**20**	**25**	**30**	**45**	**50**	**55**	**60**	**70**	**75**	**80**				
Left ear														
Masker (dB HL)	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**				
Maskee (dB HL)	**25**	**30**	**35**	**45**	**50**	**55**	**60**	**65**	**70**	**70**				
Sub. 4														
Right ear														
Masker (dB HL)	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	
Maskee (dB HL)	**10**	**15**	**20**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**80**	
Left ear														
Masker (dB HL)	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
Maskee (dB HL)	**15**	**20**	**25**	**30**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**80**	**80**

Table 2. Absolute threshold of octave masking values and level of maskee (M_e) at different masker (M_r) intensities with the frequency of masker at 500 Hz and maskee at 1 kHz-continue

Sub. 5													
Right ear													
Masker (dB HL)	45	50	55	60	65	70	75	80	85	90	95	100	
Maskee (dB HL)	25	30	35	50	55	60	65	70	75	80	85	85	
Left ear													
Masker (dB HL)	45	50	55	60	65	70	75	80	85	90	95	100	
Maskee (dB HL)	20	25	30	45	50	55	60	65	70	75	80	85	
Sub. 6													
Right ear													
Masker (dB HL)	30	35	40	45	50	55	60	65	70	75	80	85	90
Maskee (dB HL)	10	15	20	25	30	40	45	50	55	60	65	70	70
Left ear													
Masker (dB HL)	35	40	45	50	55	60	70	75	80	85	90	95	
Maskee (dB HL)	15	20	25	30	45	50	60	65	70	75	75	75	
Sub. 7													
Right ear													
Masker (dB HL)	45	50	55	60	65	70	75	80	85	90	95		
Maskee (dB HL)	25	30	35	50	55	60	65	70	75	80	85		
Left ear													
Masker (dB HL)	40	45	50	55	60	65	70	75	80	85	90	95	
Maskee (dB HL)	20	25	30	45	50	55	60	65	70	80	85	85	
Sub. 8													
Right ear													
Masker (dB HL)	40	45	50	55	60	65	70	75	80	85	90	95	
Maskee (dB HL)	10	15	35	40	45	50	55	60	65	75	80	80	
Left ear													
Masker (dB HL)	45	50	55	60	65	70	75	80	85	90	95		
Maskee (dB HL)	15	20	25	40	45	50	55	60	70	75	75		

Table 2. Absolute threshold of octave masking values and level of maskee (M_e) at different masker (M_r) intensities with the frequency of masker at 500 Hz and maskee at 1 kHz-continue

Sub. 9												
Right ear												
Masker (dB HL)	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
Maskee (dB HL)	**20**	**25**	**30**	**50**	**55**	**65**	**70**	**75**	**80**	**85**	**85**	**85**
Left ear												
Masker (dB HL)	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**
Maskee (dB HL)	**20**	**25**	**30**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**80**
Sub. 10												
Right ear												
Masker (dB HL)	**50**	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**	
Maskee (dB HL)	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**	**75**	
Left ear												
Masker (dB HL)	**45**	**50**	**55**	**60**	**65**	**70**	**80**	**85**	**90**	**95**	**100**	
Maskee (dB HL)	**25**	**30**	**35**	**45**	**50**	**55**	**70**	**75**	**80**	**85**	**80**	

to the population of sensorineural hearing loss individuals, where individuals with sensorineural hearing loss have a very low TOM [11,12]. This difference in TOM values can be explained with the help of the active and passive mechanisms in the cochlea. This explains why the normal-hearing individuals got a higher value of TOM in our experiment than in individuals with sensorineural hearing loss in the other experiments. On the other hand, the active mechanisms stop after 60 dB, after which the passive mechanism begins with no role of the cochlear amplifier [16]. In our experiment, after 50 to 60 dB the liner growth became non linear with a shift seen in the slope of the curve, thus explaining that the shift in M_r after 50 to 60 dB was due to the transition from an active mechanism to a passive mechanism, where there was a lower TOM value similar to the individuals with Sensorineural hearing loss as these individuals have only a passive cochlea in their system [12].

The active and passive mechanisms in the cochlea can also be explained using the PTCs. The width of the PTCs describes the sharpness and tuning properties of the cochlea. The width is numerically determined by a Q_{10} value the lesser the Q_{10} value, the narrower the bandwidth and sharper the tuning curve. For individuals who have normal-hearing, they tend to have sharper PTCs at lower intensities and broader PTCs at higher intensities [16]. The sharpness of PTCs can be explained due to the presence of cochlea amplifier at lower intensities that enables the active process [4].

To evaluate the frequency selectivity, tests involving estimation of auditory filter's shape such as psychophysical tuning curve [5], notched noise [17], and non-simultaneous masking [18] procedures have been used. Other non peripheral masking tests such as central masking [19], informational masking [20], overshoot phenomenon [21], and comodualtion masking release [22] have been used. In this experiment, the threshold of octave masking has been used to describe the

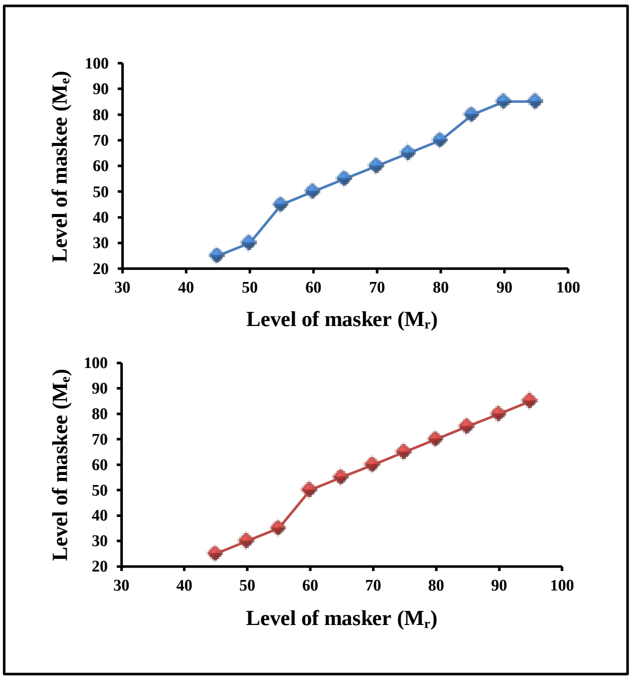

Fig. 1. Level of masker vs. level of maskee graph of a random subject (left ear: above and right ear: below) plotted to extract the intercept point and establish the threshold of octave masking.

cochlea's active and passive mechanisms. Although the tool has only been used as a predictor for noise-induced hearing loss, it can also evaluate the frequency selectivity along with peripheral and non-peripheral masking tests. The authors postulate that the shape of auditory filter can be determined based on the intercept point, more the intercept point, sharper is the intercept point.

In this study there were some limitations e.g. more number of subject sizes would have yielded more reliable results. Only normal-hearing individuals were taken as inclusion criteria. The authors were able to find differences in growth pattern after a particular intensity, a comparison with hearing impaired individuals could have been carried out to have better cognizance of the concept. As the authors comment TOM as a test to assess frequency selectivity, as a future direction, the TOM test at different frequencies must be carried out. The authors could have also performed objective test procedures like otoacoustic emissions as additional evidence to outer hair cells functioning. As future directions, professionals can try these experiments in individuals with hidden hearing loss, cochlear synaptopathy and individuals with auditory neuropathy spectrum disorders to know more about the tool's feasibility in adding it as a subjective test battery in the differential diagnosis.

Conclusion

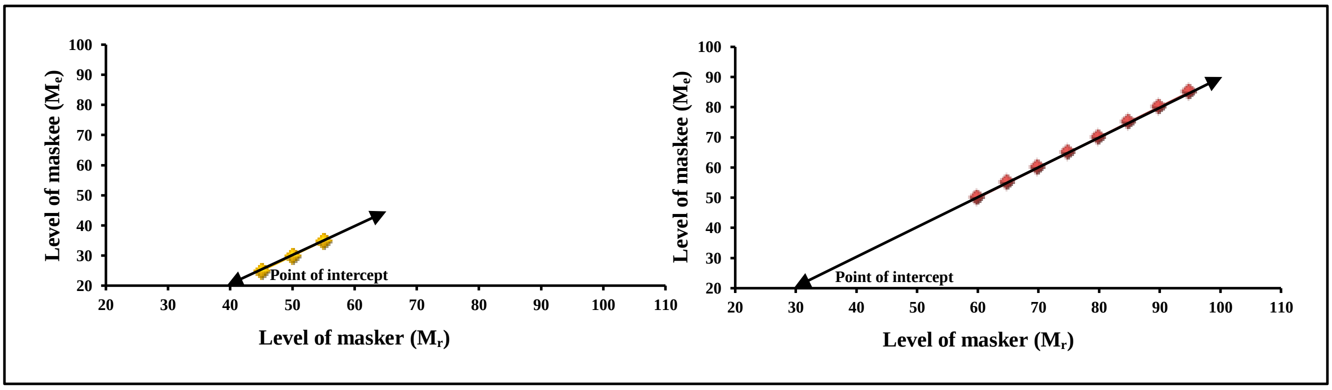

Fig. 2. Establishment of the point of interception from two extreme points. This point of intercept is considered as the threshold of octave masking. The graph left indicates the intercept point of the level of masker with respect to the initial shift in the level of maskee. The graph right shows the intercept point of the level of masker with respect to the level of maskee taken after a gap of 15 dB visualized.

Results from the present study have thrown light on the fact that TOM can be used as a tool to estimate the frequency selectivity of the inner ear based on the active and passive mechanisms of the cochlea. There have not been recent works of literature on this topic as the tool is currently not widely used in clinical practice and research. Based on our results and the fact that the tool is less time consuming than many psychophysical tests, it still can be used in current research practices, and its utility can be expanded by performing the test on different populations.

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Conflict of interest

The authors state that there was no conflict of interest.

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