CLICK EVOKED OTOACOUSTIC EMISSIONS AND DISTORTION PRODUCT IN NORMAL HEARING AND HEARING IMPAIRED ADULTS

PIYAWADEE SONTHISOMBAT

With compliments
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Click evoked otoacoustic emissions (CEOAEs) and distortion product otoacoustic emissions (DPOAEs) can help assess the functional condition of the cochlea and differentiate between normal and impaired hearing. Both CEOAEs and DPOAEs have been found to be related to hearing threshold levels. The purpose of this study was to investigate the relationship between CEOAEs and DPOAEs with a comparison to pure tone audiogram in the same group of normal hearing and hearing impaired adult subjects, and compare CEOAEs and DPOAEs amplitudes between normal hearing and hearing impaired adult subjects.

The hearing threshold, tympanogram, CEOAEs and DPOAEs were measured in 60 ears (7m/25f) with normal hearing and a mean age of 26.73 years, and in 60 ears (20m/16f) with hearing impaired and a mean age of 30.55 years. The results indicated that the CEOAEs response level, CEOAEs and DPOAEs spectrum amplitudes in normal hearing was significantly higher than those in the hearing impaired. The CEOAEs and DPOAEs spectrum amplitudes at 1, 2 and 4 kHz showed positive correlation with each other in groups of normal hearing and in group of hearing impaired (4-6 kHz notch, high frequency sloping and low frequency sloping) at $p< 0.05$. The PTT at 1-4 kHz, CEOAEs amplitudes at 1, 2 and 4 kHz and DPOAEs amplitudes at 1, 2, 4 and 6 kHz showed significant negative correlation in groups of normal hearing and in group of hearing impaired (4-6 kHz notch, high frequency sloping) at $p< 0.05$. No correlation was found between pure tone threshold at 1-4 kHz, CEOAEs amplitudes at 1, 2 and 4 kHz and DPOAEs amplitudes at 1, 2, 4 and 6 kHz in low frequency sloping and flat audiogram.

The results of this study confirmed the correlation between CEOAEs and DPOAEs in the same ear and confirmed the correlation between PTT, CEOAEs and DPOAEs. This finding suggested that CEOAEs and DPOAEs be present in normal ear having PTT better than 20 dBHL. The CEOAEs were absent when PTT was greater than 35 dBHL, and 50 dBHL for DPOAEs. Thus, the CEOAEs should be more sensitive in detecting early stages of hearing loss. However, DPOAEs showed more robustness than the CEOAEs at a high frequency component.

The differences between the occurence of the two emissions suggest that CEOAEs may be preferable for hearing screening purposes, whereas DPOAEs may be more valuable for monitoring cochlear changes clinically. Therefore, both CEOAEs and DPOAEs have the potential of becoming important parts of the basic evaluation of hearing.

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ปิยวดี สนธิสมบัติ : การวัดเสียงสะท้อนจากหูชั้นในโดยใช้เสียง click และ distortion product ในผู้ใหญ่ที่มีการได้ยินปกติและสูญเสียการได้ยิน (CLICK EVOKED OTOACOUSTIC EMISSIONS AND DISTORTION PRODUCT IN NORMAL HEARING AND HEARING IMPAIRED ADULTS) คณะกรรมการควบคุมวิทยานิพนธ์ : จันทร์ชัย เจรียงประเสริฐ, M.D.,M.Sc., ศิริพันธ์ ศรีวันยงค์, M.B.A.,M.Sc., มนต์ทิพย์ เทียนสุวรรณ, Ph.D. 107 หน้า. ISBN 974-663-191-8

CEOAEs และ DPOAEs มีประโยชน์ในการช่วยประเมินสภาวะของหูชั้นใน และบอกถึงความแตกต่างระหว่างผู้ที่มีการได้ยินปกติและสูญเสียการได้ยิน โดยพบว่า CEOAEs DPOAEs และระดับการได้ยินมีความสัมพันธ์กันวัตถุประสงค์ของการศึกษาในครั้งนี้เพื่อศึกษาความสัมพันธ์ระหว่าง CEOAEs DPOAEs และเปรียบเทียบกับผลตรวจการได้ยินทั้งในผู้ที่มีการได้ยินปกติและสูญเสียการได้ยิน เปรียบเทียบขนาดของ CEOAEs และ DPOAEs ในกลุ่มผู้ที่มีการได้ยินปกติและสูญเสียการได้ยิน ในการศึกษาครั้งนี้ตรวจวัดระดับการได้ยิน ตรวจวัดการทำงานของหูชั้นกลาง และตรวจวัดเสียงสะท้อนจากหูชั้นใน ในผู้ใหญ่ที่มีการได้ยินปกติ 60 หูอายุเฉลี่ย 26.73 ปี และผู้ใหญ่ที่สูญเสียการได้ยิน 60 หูอายุเฉลี่ย 30.55 ปี ผลการศึกษาพบว่าระดับการตอบสนองของ CEOAEs ขนาดของ CEOAEs และ DPOAEs ในกลุ่มผู้ที่มีการได้ยินปกติมีค่าสูงกว่าในกลุ่มที่มีการสูญเสียการได้ยิน มีสหสัมพันธ์เชิงบวกระหว่างขนาดของ CEOAEs และ DPOAEs ที่ความถี่1, 2 และ 4 kHz ในกลุ่มผู้ที่มีการได้ยินปกติและสูญเสียการได้ยิน(ผู้ที่สูญเสียการได้ยินที่บริเวณความถี่ 4-6 kHz, เสียที่บริเวณความถี่สูงและความถี่ต่ำ) มีสหสัมพันธ์เชิงลบระหว่างผลการตรวจการได้ยินที่ความถี่ 1-4 kHz ขนาด CEOAEs ที่ความถี่ 1, 2, 4 kHz และขนาด DPOAEs ที่ความถี่ 1, 2, 4, 6 kHz พบว่าในกลุ่มผู้ที่มีการได้ยินปกติและ สูญเสียการได้ยิน(ผู้ที่สูญเสียการได้ยินที่บริเวณความถี่ 4-6 kHz, เสียที่บริเวณความถี่สูง) ในการศึกษาครั้งนี้ไม่พบความสัมพันธ์ในกลุ่มผู้ที่มีการสูญเสียการได้ยินที่บริเวณความถี่ต่ำและflat

ผลการศึกษาครั้งนี้ยืนยันว่า CEOAEs และ DPOAEs มีความสัมพันธ์กันในหูคนคนเดียวกัน และมีความสัมพันธ์กับระดับการได้ยิน พบว่าทั้ง CEOAEs และ DPOAEs จะปรากฏในผู้ที่ระดับมีการได้ยินน้อยกว่า 20 เดซิเบล เมื่อระดับการได้ยินมากกว่า 35 เดซิเบลจะตรวจไม่พบ CEOAEs และเมื่อระดับการได้ยินมากกว่า 50 เดซิเบลจะตรวจไม่พบ DPOAEs จะเห็นได้ว่าCEOAEsมีความไวในการบอกการสูญเสียการได้ยินในระยะเริ่มแรก ดังนั้นCEOAEs จึงเหมาะกับการตรวจคัดกรองการได้ยิน แต่การได้ยินที่ความถี่สูง DPOAEs มีขนาดใหญ่กว่า CEOAEs ดังนั้น DPOAEs จึงเหมาะกับการเฝ้าติดตามการเปลี่ยนแปลงของหูชั้นใน

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CHAPTER I

INTRODUCTION

The otoacoustic emissions (OAEs) are acoustic energy generated by the haircells in the cochlea and propagated backward into the external ear canal through the ossicles and the tympanum (1,2). The first measurements of OAEs were reported in 1978 by David Kemp from Institute of Laryngology and Otology (ILO), England.

There are two broad classes of OAEs: spontaneous and evoked. Spontaneous otoacoustic emissions (SOAEs) are narrowband signals which can be recorded in the external ear canal in absence of external acoustic stimulation (3).SOAEs can be detected in about 50% of normal hearing humans or in approximately 40% of their ears (4). Evoked otoacoustic emissions (EOAEs) occur during or after presentation of an external acoustic stimulus. There are three types of EOAEs distinguished primarily by the stimuli used to evoke them.Transient evoked otoacoustic emissions (TEOAEs) occur after the presentation of a brief acoustic stimulus including clicks and tone bursts (1). Stimulus frequency otoacoustic emissions (SFOAEs) are continuous tonal emissions evoked at the same frequencies as the continuous pure-tone stimuli. Distortion product otoacoustic emissions (DPOAEs) are the acoustic form of the difference tones that are produced by the cochlea during simultaneous stimulation with the two continuous pure tone at f1 and f2 in which f1 represents the lower frequency stimulus or primary tone and f2 the higher frequency primary. The DPOAEs at the frequency 2f1-f2 is the most prominent DPOAEs in the human ear (4,5,6,7).

Among the different classes of OAEs, click-evoked otoacoustic emissions (CEOAEs) have been the most studied, probably because of their ease of recording and their presence in almost all normal hearing ears (8). Moreover correlations between audiogram and CEOAEs spectrum have been studied by several authors (9,10,11). In normal hearing subjects, the detection threshold of CEOAEs is generally equal to the mean audiometric thresholds for the frequencies 1,2, and 4 kHz. In hearing-impaired subjects CEOAEs have never been observed when mean audiometric thresholds were equal to or greater than 30 to 35 dBHL. The incidence of CEOAEs decreases linearly with increasing audiometric threshold (12).

A number of studies have investigated DPOAEs in human to determine whether the DPOAEs can help assess the functional condition of the cochlea and differentiaed normal hearing from hearing-impaired (10,13,14,15). In normal hearing subjects the DPOAEs can be recorded from 90 to 100%. The general pattern of DP-gram can be detected is between 0.5 and 8 kHz, with a maximum incidence between 1 and 2 kHz and difficult to test at the frequencies below 1 kHz. The most prominent emissions at 1 and 2 kHz may reflect the frequency dependent efficiency of the middle ear to transmit energy both in the forward and reverse direction. At lower frequencies, the DPOAEs measurement is interfered by noise (5,6,13,14). In hearing-impaired subjects, the DPOAEs are absent when thresholds exceeded 50 to 60 dBHL (15,16,17). Reliability of threshold detection for DPOAEs depends almost entirely on the noise floor, the difference in the equipment and methods of DPOAEs recording (5).

Both CEOAEs and DPOAEs are found to be related to hearing threshold levels, an interrelation of the two emission types will be expected. In general, when one type of OAE is present, the other will be also. The overall levels of the two responses are correlated (18). The high correspondence of response amplitudes also occurs in ears with threshold levels better than 20 dBHL. CEOAEs are dominated by components in the mid-frequency range, therefore effective in sampling cochlear functioning in that range. DPOAEs can be measured over a broad range of frequencies, but they are present in the high frequencies more often than are CEOAEs (2).

This paper aim to investigat the relationships between CEOAEs and DPOAEs with a comparison to pure tone audiogram in the same group of normal hearing and hearing-impaired subjects.

Purposes of This Study

1. To compare the CEOAEs response level in normal hearing and hearing impaired adults.

2. .To compare the CEOAEs spectrum amplitudes in normal hearing and hearing impaired adults

3. To compare the DPOAEs amplitudes in normal hearing and hearing impaired adults

4. To study the relationship between the CEOAEs spectrum amplitudes and DPOAEs amplitudes in normal hearing adults

5. To study the relationship between the CEOAEs spectrum amplitudes and DPOAEs amplitudes in hearing impaired adults

6. To study the relationship between CEOAEs spectrum amplitude by half octave analysis and DPOAEs amplitude at different f2 (DP gram) with pure tone audiometric thresholds in normal hearing adults.

7. To study the relationship between CEOAEs spectrum amplitude by half octave analysis and DPOAEs amplitude at different f2 (DP gram) with pure tone audiometric threshold in hearing impaired adults.

Research Questions of This Study

This study intends to answer these following questions:

1. Was there any difference of the CEOAEs response level in normal hearing and hearing impaired adults?

2. Was there any difference of the CEOAEs spectrum amplitudes in normal hearing and hearing impaired adults?

3. Was there any difference of the DPOAEs amplitudes in normal and hearing impaired adults?

4. Did the correlation exist between the CEOAEs spectrum amplitudes and DPOAEs amplitudes in normal hearing adults?

5. Did the correlation exist between the CEOAEs spectrum amplitudes and DPOAEs amplitudes in hearing impaired adults?

6. Did the correlation exist between the CEOAEs spectrum amplitudes and DPOAEs amplitudes at difference f2 with pure tone thresholds in normal hearing adults?

7. Did the correlation exist between the CEOAEs spectrum amplitude and DPOAEs amplitude at difference f2 with pure tone thresholds in hearing impaired adults?

The Expected Outcomes of This Research

1. The result of this study may be used as a guideline in using OAEs for evaluation in SNHL

2. The result of this study may be used as a guideline to differentially diagnostic between cochlear hearing loss and retrocochlea hearing loss

CHAPTER II

LITERATURE REVIEW

In this chapter, the basic knowledge in three major areas: anatomy of the cochlea and cochlea mechanics, click-evoked otoacoustic emission (CEOAEs) and distortion product otoacoustic emissions (DPOAEs) were reviewed. Besides their basic characteristics and recording parameters, have been included some of the clinical applications, clinical study of CEOAEs and DPOAEs in hearing impaired, and the interrelation between each type of OAEs.

1. Anatomy of the cochlea

The human cochlea is about 35 mm. long, and form a somewhat coneshaped spiral with two and a half turns. It is widest at the base, where the diameter is approximately 9.0 mm., and tapers toward the apex. The cochlea is divided lengthwise into three channels: the scala media or cochlea duct, scala vestibuli, and scala tympani by the basilar membrane and the Reissner's membrane, respectively (Figure 1). The scala media is enclosed within the membranous labyrinth and contains endolymph, which is a unique extracellular fluid low in sodium and high in potassium. The scalae vestibuli and tympani, communicate with one another at the apex of the cochlea, through an opening called the helicotrema. The scalae vestibuli and tympani are filled with perilymph, which is a typical extracellular fluid high in sodium and low in potassium. The scala vestibuli is in contact with the stapes at the oval window, while the scala tympani has a membrane covered contact with the middle ear at the round window (18,19,20,21).

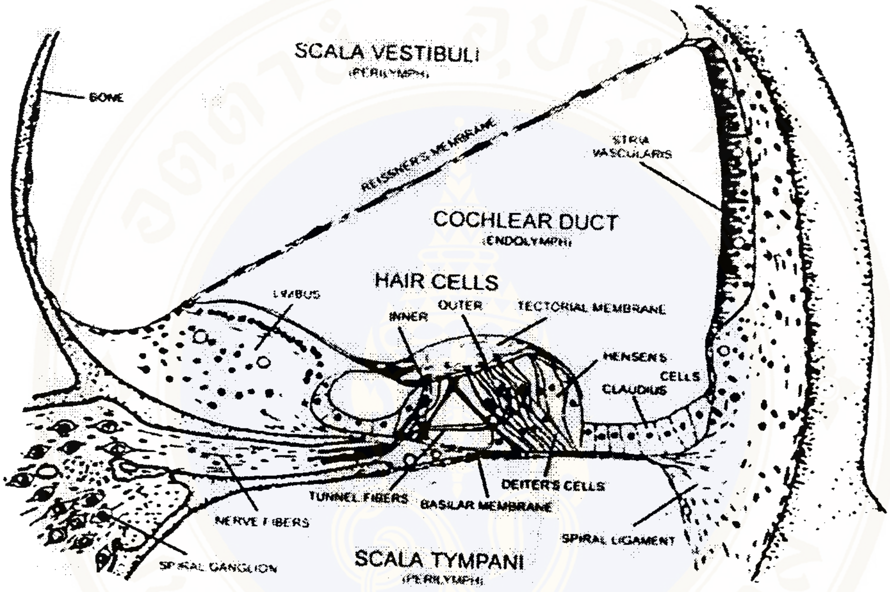

Figure 1 A cross-section of the central portion of the cochlea cavity (22).

Organ of Corti

The organ of Corti, lies within the scala media, rests on the osseous spiral lamina and basilar membrane. Grossly, it is made up of a single row of inner hair cells (IHCs), three (sometime four) rows of outer hair cells (OHCs), various supporting cells, and the pillar cells forming the tunnel of Corti. The organ of Corti is given rigidity by an arch of rods or pillar cells along its length. The arch is surrounded by phalangeal cells; the inner phalangeal cells completely surround the IHCs. The outer phalangeal cells, which are also known as Deiters' cells, form cups holding the basal ends of the OHCs and send fine processes, or phalanges, up to the reticular lamina, leaving spaces between the OHCs. External of the OHCs there is a row of supporting cells known as Hensen's cells, and on the modiolar side of the organ of Corti there is a further row of supporting cells (18,23).

The organ of Corti is covered by a gelatinous and fibrous flap, the tectorial membrane. The tectorial membrane is fixed only at the limbus medially and more loosely attached laterally at the border net above the Hensen's cells. The tallest cilia on the OHCs are shallowly but firmly embedded in the under surface of the tectorial membrane. The IHCs cilia are probably not embedded and fit loosely into a raised groove known as Hensen's stripe on the under surface of the tectorial membrane (18,19,22,24).

The tectorial membrane is attached only on one side and is raised above the basilar membrane. Therefore, when the basilar membrane moves up and down, a shear or relative movement will occur between the tectorial membrane and basilar membrane. The resulting motions shear the longest OHCs cilia so that they bend outward (away from the modiolus) when the membranes are deflected upward resulting in depolarization of the hair cell (Figure 2).

The IHCs, which do not appear to contact the tectorial membrane, are probably stimulated by fluid streaming between the two membranes and through their stereociliary arrays. The fluid is set in motion by relative movement between the tectorial and the organ of Corti (21,25,26).

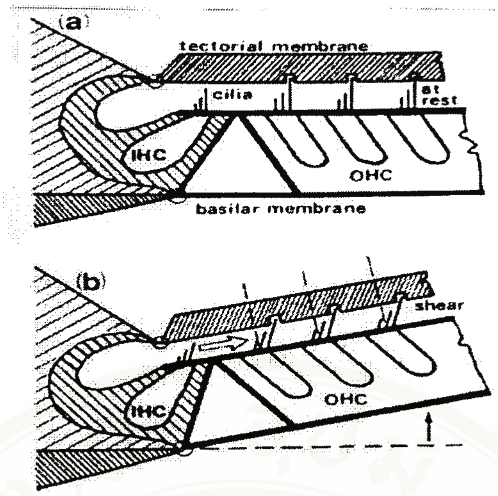

Figure 2 Relative positions of the basilar membrane and tectorial membrane at rest (a) and during elevation towards the scala vestibuli (b).(18)

Inner verus Outer hair cell

In the human cochlea, there are approximately 12,000 inner hair cells (IHCs) and 3,500 outer hair cells (OHCs). The IHCs are flask shaped with the nucleus is center. The stereocilia on IHCs are arranged in three slightly curved rows. The IHCs are contacted with 90 to 95 % afferent auditory nerve fibers (type I neuron), and each IHC has terminals from about 15-20 afferent fibers. Therefore the role of IHCs is to detect the movement of the basilar membrane and transduce that movement into electrical potential in the auditory nerve (19,23,25,26)

The OHCs are cylindrical shaped, with the nucleus located basally. The stereocilia on OHCs are arranged in three to four rows in a W-shaped pattern. The OHCs are contacted with the afferent auditory nerve only 5 to 10 % (type II neuron). Each type II neuron branches to innervate approximately 10 OHCs. Therefore OHCs are probably involved in generating the active mechanical amplification of basilar membrane vibration, which gives rise to the relatively large amplitude and sharply tuned mechanical traveling wave and also generate the cochlea microphonic (31,33).

2. Cochlear Mechanics

2.1 Traveling wave

The cochlea is a complex hydromechanical system activated by the motion of the stapes footplate. Inward motion of the footplate results in displacement of fluid within the scala vestibuli. If this movement were to occur extremely slowly, the fluid in the scala vestibuli would simply be shunted through the helicotrema into the scala tympani, resulting in outward movement of the round window membrane. However, when stapes movement is rapid (> 10 to 20 Hz), it is opposed by the inertia of the fluid mass as well as by the frictional resistance generated by the fluid flow within the narrow scala. This opposition to flow results in a pressure gradient across the basilar membrane. When the stapes is displaced inward, the basilar membrane bulges into the scala tympani, leading to the outward movement of the round window membrane. Rapid inward and outward motion of the stapes thus leads to an alternating pressure gradient that is propagated along the entire length of the cochlea almost instantaneously (23). If the cochlea is viewed over its entire length, the wave motion would appear of a “traveling wave”.

Because of the structure characteristics of the cochlear, the traveling wave does not maintain a uniform amplitude throughout the cochlea. From its origin at the base, it increases in amplitude while progressing toward the apex until it reaches a maximum, beyond which it declines rapidly (Figure 3). Moreover, the location along the cochlea at which the traveling wave reaches its largest amplitude changes with the frequency of the stimulating signal. High frequency stimuli generate the maximum wave amplitude at the base of the cochlea. For lower frequencies, the maximum amplitude of displacement is found toward the apex (20,21,23,27,28).

This difference in the behavior of the partition to different frequencies of stimulation is due to its peculiar structure. Because of the base to apex changes in width, mass, and especially stiffness, the ability of the partition to absorb energy from high frequency changes in fluid pressure is diminished toward the apex. Thus, high frequency energy excites only the basal region, where as the low frequency energy is allowed to travel further along the cochlea (20,21).

Stuhlman (29) established relation between of sound waves and position of maximum mechanical movement. The highest audible frequency about 20,000 Hz is associated with the extreme basal end of the membrane just behind the round window. The frequency of 2,000 Hz lies at the midpoint along the basilar membrane between base and apex. The apical end of the membrane at the helicotrema is reached at about 60 Hz.

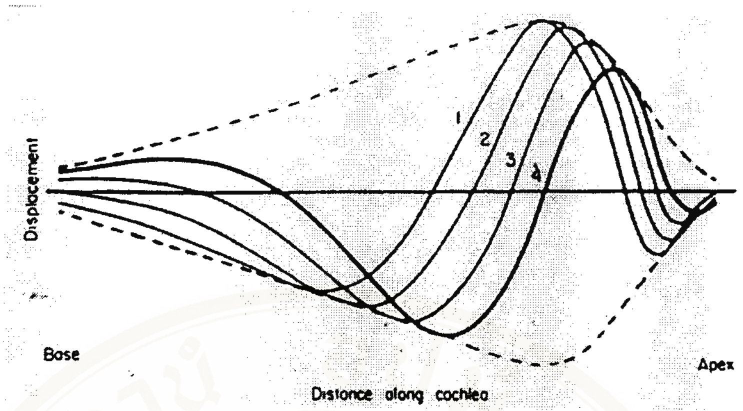

Figure 3 The traveling wave produced by a 200 Hz tone. The solid lines show the displacement of the wave form the base toward the apex (24).

2.2 Hair Cell Transduction

Transduction process begins with the conversion of the mechanical input and ends with the output of neural discharge in afferent nerve (27). This transduction is response by cochlea hair cell, for the actual translation of mechanical vibrations into electrochemical phenomena that precede the generation of nerve impulse. Hudspeth (33,34) studied cochlea transduction process, that the individual stereocilia on the apical surface of the hair cell are mechanically rigid, and were braced together with cross-links so that they move as a stiff bundle. Therefore, as the bundle is deflected, the different rows of stereocilia could be expected to slide relative to one another. There are fine links running upwards from the tips of the shorter stereocilia on the hair cell, which join the adjacent taller stereocilia of the next row by a flexible link. When the stereocilia are deflected in the direction of the tallest stereocilia, tension is created in the transduction link, the links are strecthed, opening ion channels in the cell membrane, allowing potassium (K^+) to flow into the hair cell (depolarization). When the bundle is deflected in the opposite direction, ion channels is closed, reducing the influx of K^+(hyperpolarization).

2.3 Active Process within the cochlea

There is considerable evidence that active processes occur in the cochlea, and there is evidence that outer hair cells can generate movement. Because the motile activity of OHCs is assumed to be the basis of the cochlear amplifier, that is responsible for the high sensitivity and sharp of selectivity of the ear (36). The most direct evidence for the existence of active processes comes from the study of the cochlear emissions (25). The study showed that under certain circumstances the cochlea can produce sound, and that this appeared to be related to the activity of the hair cells themselves (Figure 4). Acoustic power entering the cochlea induces a pressure difference across the basilar membrane and a traveling wave motion that propagates from the basal end towards the apex (A). Displacement of the basilar membrane causes deflection of the stereocilia of the OHCs (B), which in turn modulates the current through the OHCs (C). The next stage (D) is less well-understood, but some sort of mechanical motion is induced in the OHCs and this produces a direct effect on the basilar membrane in such a way as to assist the original displacement. This loop, A-B-C-D-A, is the cochlea amplifier: stage C is known as the forward transduction, or mechanical-to-electrical transduction, and stage D is known as the reverse transduction, or electrical-to-mechanical transduction (35).

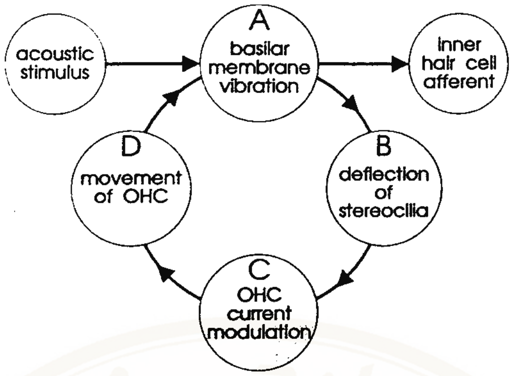

Figure 4 Diagram representation of the active process within cochlea (35)

Both CEOAEs and DPOAEs are generated within the inner ear by the same active, nonlinear process underlying the sensitivity and selectivity mechanisms of the cochlea. These emitted responses assumed to be generated by the stimulus-induced motility of the OHCs (37). When the ear is stimulated with a click, the cochlea return an acoustic echo to the external auditory meatus, which can have more energy than was originally introduced. Analogous echoes can be seen with other types of stimuli. If, for instance, the ear is stimulated with a continuous tone, the cochlea reflects a tone back into the ear canal. With two-tone stimulation, acoustic distortion products produced by intermodulation between the stimulus tones can be detceted in the ear canal (25).

2.4 Cochlear electrical potentials

Cochlear electrical potentials consist of three components, the endocochlear potential (EP), the cochlear microphonic (CM), and the summating potential (SP). Whereas the EP is present at rest; the CM and SP appear only when sound stimulates the ear.

(1) Endocochlea potential (EP)

The EP is a large positive potential, in the absence of any acoustic stimulus of approximately +80 mV to +100 mV. This potential is maintained by a combination of active ionic pumps and selectively permeable ion channels in the cells of the stria vascularis (22,23,28,30,32). The EP is susceptible to metabolic disturbances such as anoxia and chemical agents interfering with oxidative metabolism (28), or diuretic with ototoxic property such as ethacrynic acid (23,33).

(2) Cochlear microphonic (CM)

The CM is an alternate current (AC) potential that follows the waveform of the stimulus. The CM is produced by the outer hairs (1).If the OHCs are destroyed by the ototoxic agents such as streptomycin, kanamycin, the response will drop drastically (22,25,32).

The amplitude of the CM is spatially distributed along the cochlear partition according to frequency. The maximum CM is recorded near the base of the cochlea for high frequencies, whereas the maximum CM is recorded near the apex of the cochlea for low frequencies. Moreover, the amplitude of the CM is proportional to stimulus level. At low intensities, the CM amplitude increases linearly with a slope of one. At high intensities, the CM contains a considerable amount of harmonic distortion and may bear little resemblance to the input signal (23,32).

(3) Summating potentials (SP)

The SP is a shift in the direct current (DC) baseline in response to sound stimulation. The SP, like the CM, is stimulus-related and a product of hair cell generator. Unlike the CM, however, the SP is seen as DC voltage that appears to be representative of the stimulus envelop rather than its waveform. The polarity of the DC shift may be positive or negative depending on the frequency and intensity of the acoustic stimulus and the site of the recording electrode (41).

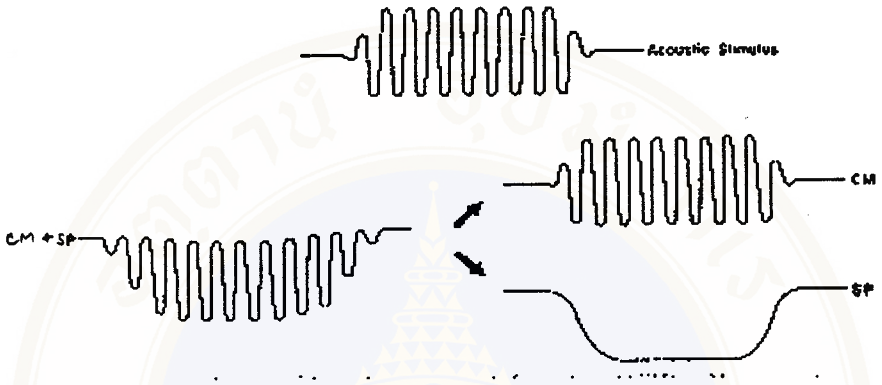

Figure 5 The cochlear microphonic (CM) and summating potential (SP) response to a pure-tone stimulus. The top of the figure shows a short tone burst applied to the eardrum. The lower panels show responses recorded from the cochlea (25,30).

3. Otoacoustic Emissions

The otoacoustic emissions (OAEs) are defined as a sound produced in the cochlea that can be recorded in the external ear canal. They represent an objective measurement of the active mechanical processes assumed to be generated by the outer hair cells of the organ of Corti (38).

Classification of Otoacoustic emissions

According to Probst et al (5), the classification of OAEs were briefly described. Two major classes of OAEs are spontaneous and evoked OAEs which can be subclassified according to the evoked stimuli.

1. Spontaneous OAEs (SOAEs)

SOAEs consists of narrow band signals that can be measured in the absence of external acoustic stimuli. They can be detected as low-level tones in about 40-50 % of normal hearing ears (5,34).

2. Stimulated or Evoked OAEs (EOAEs)

EOAEs occur during or after presentation of an external acoustic stimuli. They can be detected in nearly or normal hearing ears (1,34,35). There are three types of EOAEs distinguished primarily by the stimuli used to evoke them.

2.1 Transient evoked OAEs (TEOAEs)

TEOAEs are elicited by brief acoustic stimuli such as clicks or tone pips. TEOAEs exhibit characteristics typical of most evoked OAEs respect to stimulus onset.

2.2 Stimulus frequency OAEs (SFOAEs)

SFOAEs are continuous tonal emissions evoked at the same frequencies as the continuous pure tone stimuli.

2.3 Distortion product OAEs (DPOAEs)

DPOAEs are the acoustic form of the difference tones that are produced by the cochlea during simultaneous with the two continuous pure tone at f1 and f2 in which f1 represents the lower frequency stimulus or primary tone and f2 the higher frequency primary.

Transient Evoked Otoacoustic Emissions (TEOAEs)

TEOAEs can be evoked by any brief transient stimuli which click is the most common and widely used. Click stimuli can stimulate nearly the whole cochlea, consists a wide power spectrum which will give information over wide frequency range up to 5 kHz (39,40).

3.1 Click-Evoked OAEs (CEOAEs)

Click stimuli, which are very short usually 80 μsec rectangular pulse but strong broadband stimuli, are presented in a sweep pattern. One sweep has 4 clicks which consists of 3 isoamplitudes condensation clicks and one rarefaction click with 3 times greater in amplitude. When they are added together, it will cancel out the linear response from the outer, middle and some from the inner ear. This technique is called "Linear Cancellation" (Figure 6) (23).

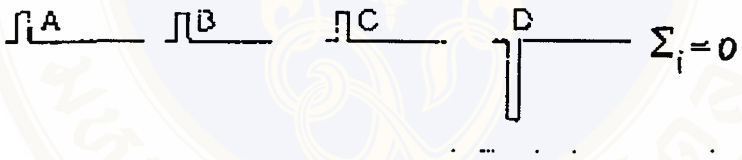

Figure 6 Pattern of non-linear stimulus mode. The stimuli are presented in groups of four. The first three clicks in each group are presented in condensation. The fourth is produced in the rarefaction and three times larger amplitude. The sum of linear response will be zero.

The linear cancellation has several advantages. First, middle ear artifacts which could easily be misinterpreted as a residual otoacoustic emission in a truly deaf ear will be removed. Second, the patient and external noise signals can be trapped at much lower levels and at short latencies. Third, the high frequency, low latency emissions can be more clearly recorded. Fourth, high levels of stimulation can be used, which increases the level of emission, and results in greater uniformity and a wider frequency range of response (38,39,40).

Basic characteristics

1. Waveform

The response waveform of CEOAEs is divided into two sections. The initial component, 0-5 ms after the stimulus onset, is attributable mainly to the impulse response of the transducers but also to that of the outer, middle ear and the passive response of the cochlea. This component increases in amplitude linearly with increasing stimulus amplitude. The second part of the response waveform usually begin 3 ms or more after the stimulus depending on the impulse response of the probe. The waveform in this period is small in amplitude and clearly displayed only after the linear impulse response has decayed (40,41).

The CEOAE waveform often have the general appearance of bursts of oscillation, each dominated by one frequency but other less periodic waveforms often occur. The typical frequency spectrum of the response is 0.5 – 4 kHz, most emission energy in adult fall in the octave band 1-2 kHz. The frequency band of the most prominent emissions is correspond to the frequency range of most efficient transmission through the middle ear, in both directions (7). The CEOAE waveform tends to exhibit frequency dispersion such that the higher frequency component usually occur at the beginning of the waveform. As the latency increases the frequency of the components decreases as a consequence of the tonotopic organization of the cochlea. This frequency dispersion has been assumed to reflect the time taken by the forward travelling wave of the stimulus along the basilar membrane to the site of generation of the OAE, plus the travel time of the reverse travelling wave to the oval window (1,42,43).

2. Amplitude

The amplitude of CEOAEs depends on stimulus level, frequency response of both the middle ear and the recording system. The amplitudes of the CEOAEs are usually small, less than 20 dBSPL and increase with increasing level of stimulation. At very low stimulus level, the increase is linear, and becomes saturated at more intense stimuli (1). CEOAEs in general have the greatest amplitude between 1000 and 1500 Hz frequency band. Kemp et al (44) suggested that the frequency spectrum of CEOAEs reflected the middle ear transfer function with transmission efficiency best in the 1000 to 1500 Hz range and a transmission lossed of about 12 dB per octave for lower and higher frequencies.

3. Latency

CEOAEs appear in the human ear canal with a specific latency that depends on the frequency of the emission. The high frequency stimulation elicited CEOAEs with shorter latencies than those evoked by low frequencies (4,5). The latency of human OAEs was around 4 msec for 5 kHz to 20 msec to 500 Hz, or obviously 10 msec at 1 kHz to 1 msec at 10 kHz (41).

Responses

The main responses of a CEOAEs that have been investigated consist of CEOAEs response level, CEOAEs spectrum amplitude and their association with audiometric outcomes.

1. CEOAEs response level

The CEOAEs response level is calculated from an root mean square (RMS) calculation of the average of the two traces (A, B) and converted to dBSPL using the calibration appropriate to the probe. This represents the mean energy of the two averaged responses, in the 20 msec time window (45).

Several investigations studied normal ranges of CEOAEs response level in normal hearing adults (45,46,47,48,49,50). Most of the clinical records of CEOAEs using ILO 88/92 Otodynamic analyzer, 80 µsec rectangular pulse presented at a rate of 50/sec at 78 to 84 dBSPL nonlinear click stimulus, band pass filter 500 to 5000 Hz. The average CEOAE response level ranged from 9.2 to 12.1 dBSPL. The CEOAE response level tended to decrease or absent as the hearing threshold increased (47). Kemp et al (44) showed a gradual decrease in acoustic emission level with sensory hearing loss with roughly ≅ 10 dBSPL loss in emission level for a 10 dBHL loss of hearing.

Glattke et al (47) measured CEOAEs response level from 130 ears with hearing threshold more than 20 dBHL from 250-8000 Hz. The average CEOAE response level was 2.6 dBSPL (SD = 4.8). As well as Qiu et al (50), they examined in a group of 43 patients with mild SNHL and 27 patients with moderate to severe SNHL They found that, the means (SD) of CEOAEs response level were 2.7 (5.3) and 0.2 (0.8) dBSPL, inspectively.

2. CEOAEs spectrum amplitude

CEOAEs spectrum amplitude is calculated as the ratio of signal and noise at the same half-octave frequency. The spectrum of signal exceed that of noise more than

3 dBSPL. The amplitude spectrum of a CEOAEs depend on several factors, including the spectral energy of the stimulus, the duration of the averaged time period, and the structurally dependent resonances unique to an individual ear (5). When a broadband stimulus is applied and the elicited response is averaged over a relative long time period, CEOAEs shows spectra containing several discrete (dominant frequencies). CEOAEs spectrum contains several dominant frequencies which occur especially within a 1 kHz to 4 kHz frequency range. Maximum amplitudes in adults usually fall in the octave band of 1-2 kHz (47, 51, 52).

Fuse et al (53) studied normal range of a CEOAEs spectrum determined by 42 adults with normal hearing and compared with 46 ears (34 subjects) with sensorineural hearing loss (SNHL). In normal hearing, the CEOAE spectrum sloped down at high frequencies and amplitude of the CEOAE spectrum to be correlated with the audiogram. In SNHL, the CEOAE spectrum amplitudes were found to lower than normal ears at 0.5, 1 and 2 kHz.

Hauser et al (52) reported CEOAEs spectrum amplitude in 20 normal hearing and 20 subjects with high frequency sensorineural hearing loss. In the ear with high frequency sensorineural hearing loss, CEOAEs spectrum amplitude was not detected above 2 kHz. In the lower frequency range up to 2 kHz, where the hearing of both groups was normal, ears with high frequency sensorineural hearing loss showed emission of much lower amplitudes than normal hearing which were 4.2 ± 2.5, 12.1 ± 5 dBSPL respectively.

Bonfils and Uziel (12) studied CEOAEs spectrum amplitude in 85 ears with high frequency sensorineural hearing loss of various causes. They found that CEOAEs spectrum amplitude was always present in the 0.7 to 1.5 kHz band, with a mean maximum amplitude occuring at 1.1 kHz.

Kubo et al (53) studied CEOAEs spectrum amplitude in 5 ears with normal hearing and 22 ears from patients with Meniere's disease. They found that, the main frequencies in ears with Meniere's disease ranged mainly from 0.8 kHz to 1.1 kHz and were to be found at lower frequencies than in ears with normal hearing whose range was mainly from 1 kHz to 1.6 kHz. Furthermore, in some ears with Meniere's disease, the main frequencies changed from lower to higher after administration of osmotic diuretics such as glycerol or isosorbide.

Hotz et al (54) measured CEOAEs in 117 males recruits and 30 male career in compulsory military service in Switzerland. CEOAEs were measured before and at end of a 17 weeks training period that included exposure to noise from firearms. Results revealed significant changes in response amplitude in the frequency range from 2 to 4 kHz, whereas changes in the frequency range from 0.5 to 2 kHz were not significant for either group.

3. CEOAEs spectrum amplitude and pure tone audiogram

The CEOAEs and hearing threshold levels are both derived following stimulation to the cochlea. Thus, CEOAEs and pure tone results do relate to one another because they share features of a common mechanism. If this mechanism is functioning normal, then the parameters derived from both measures are generally within some grossly normal range. An abnormal mechanism affects both measures e.g., middle ear disorders (18).

In normal hearing, the contour of CEOAEs spectrum approximates the audiogram. Where the audiogram shows frequency bands of normal hearing, CEOAEs response are usually evoked at those frequencies. However, the contour of the CEOAE spectrum usually approximates the audiogram in the range of 0.5 to 4 kHz (6, 41, 54). In hearing-impaired subjects CEOAEs have never been observed when mean audiometric thresholds were equal to or greater than 30 to 35 dBHL. The incidence of CEOAEs decreases linearly with increasing audiometric threshold (12).

Collet et al (55) evaluated CEOAEs spectra and audiograms from 150 patients with pure sensorineural hearing loss and found significant correlation with frequency. The greater the number of spectral components at high frequencies in CEOAEs, the better the hearing threshold of the subjects at higher frequencies appearing on the audiogram. However, they noted that the hearing threshold and the configuration of the hearing loss were significant influences on the CEOAEs and cautioned against making simple comparisons in a frequency by frequency manner.

Attias et al (56) examined the association between the audiometric hearing thresholds and CEOAEs spectral amplitudes in 129 adult subjects with and without a noise-induced hearing loss. They found that CEOAE levels decreased as the hearing threshold increased at each of the test frequencies. CEOAEs were not detected at frequencies where the hearing thresholds exceeded 20 dBHL. In noise-induced hearing loss, the CEOAE spectral frequency was found to precede or equal the corresponding frequency of pure tone hearing loss at 1 nHz. As well as Reshef et al (57), They examined in a group of 61 ears with normal hearing and 72 ears with noise induced hearing loss (NIHL). They found that, the NIHL group the mean overall CEOAEs level was lower than in the normal hearing group. Moreover, in 94% of the ears with

NIHL, the frequency at which the hearing loss began was at or above the frequency of the last peak in the CEOAEs spectrum.

Hauser et al (52) reported a study of 60 subjects with either normal hearing or high frequency sensorineural loss. They found that the results for the two groups were clearly different from each other above approximately 2 kHz. Additionally, the CEOAEs spectrum amplitude at 0.5 to 1 kHz from the ears with high frequency sensorineural loss were lower in level than the grouped results from the ears with normal hearing, even though their hearing levels were comparable in this range.

Lind and Randa (58) studied in 32 adult subjects with either high or low to medium frequency hearing loss. They found that if hearing was better than 25 to 30 dBHL at 2 kHz, then a response would be present, despite the configuration of the hearing loss.

CEOAEs and Pure-Tone results

The CEOAEs and hearing threshold levels are both derived following stimulation to the cochlea. However, they do not test the cochlear response in the same way. For measuring CEOAEs, the ear is stimulated by clicks that are usually presented at suprathreshold levels. This results in a generalized response from the cochlea that is composed of contributions from sources that are distributed along the cochlea partition (59). The CEOAE has no true threshold because its measurement is always constrained by the noise floor of the measuring system. By contrast, a hearing threshold is the point where a listener can just detect the presence of a signal at some predefined criterion rate (such as 50% or 75%). A true threshold is obtained for the stimulating signal. Despite these methodological differences, CEOAEs and subjective detection threshold do relate to one another because they share partly features of a common mechanism. If this mechanism is functioning normally, then the parameters derived from both measures are generally within some grossly normal range. An abnormal mechanism can affect both measures e.g., middle ear disorders (18).

The outcomes of the majority of investigations that have been designed to determine the cutoff levels of hearing that can be identified with CEOAEs are summarized in Figure 6 (1,5,10,11,37,45). There are two distinct situations in which the association of CEOAEs and hearing is straightforward. Segment A represents that when overall hearing is better than 20 dBHL, CEOAEs are present in 99% of ears. Segment C represents that when SNHL greater than 40 dBHL with no complicating etiological factors; CEOAEs are always absent. Segment B is considered as a zone of uncertainly that extends from approximately 25 to 35 dBHL. In this range,CEOAEs may be present but are generally reduced in amplitude and in frequency content in comparison to findings from ears with thresholds falling within Segment A. In the presence of a small amount of hearing loss, a CEOAE may still be measured. It is not certain that a linear relationship exists between decreases in pure tone threshold and the level and reproducibility of CEOAEs can assist in their interpretation because a fragmented response is often associated with partial hearing loss (18).

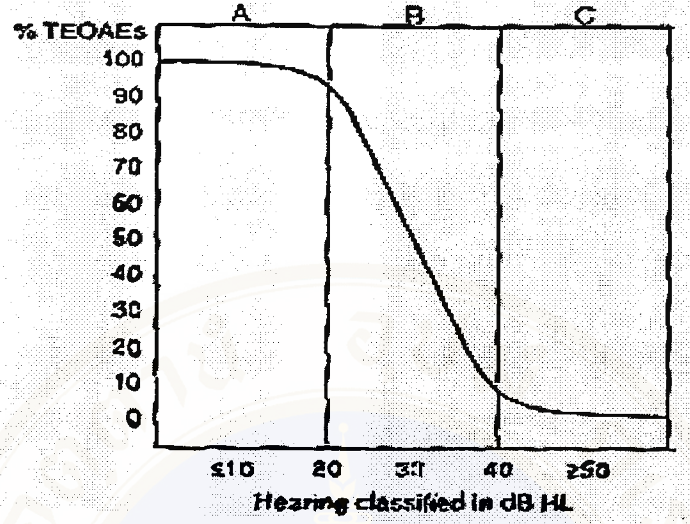

Figure 7 Schematic representation of the average pure tone results associated with percentage of CEOAEs present (18)

Clinical Applications

Clinical use of CEOAEs has become increasingly acceptable because the test is non-invasive, objective, and easily administered. CEOAEs are present in essentially all normal ears, but are usually absent or reduced in amplitude in frequency regions of cochlear dysfunction (1,6). Thus, CEOAEs show great potential for use in clinical applications including detection of hearing loss in infants, differential diagnosis of certain types of sensorineural hearing loss, and monitoring of cochlear condition over time in subjects at-risk for cochlear impairment, e.g., patients receiving ototoxic medications, exposure to noise.

Distortion Product Otoacoustic Emissions (DPOAEs)

Distortion Product Otoacoustic Emissions (DPOAEs) occur when the ear is stimulated by two pure tones, slightly different in frequency (3,59). These pure tones typically are called primaries and are labeled f1 and f2, with f2 slightly higher in frequency than f1. In human with normal auditory function, a ratio between f2 and f1 of 1.22 tends to produce the largest distortion products (60,61). Many distortion products may be generated by the human cochlea, but the largest distortion product occurs at a frequency equal to 2f1–f2, which is known as the cubic distortion product (4,5,36).

The DPOAE can be recorded in 90 to 100 % of normal ears. The general pattern of curve is very consistent with high test/retest reliability. The reliable frequency range which DPOAEs can be detected is between 0.5 and 8 kHz, with a maximum incidence between 1 and 2 kHz (5) and difficult to test at the frequencies below 1 kHz (6). According to the most effective reverse transmission of the middle ear, the DPOAE seem to be present within the same frequency range as the other classes of OAEs.

Basic characteristic

1. Amplitude

The DPOAE is generally of smaller amplitude than the other types of stimulated OAE, approximately 60 dB smaller than the levels of the eliciting stimuli (5). It has been found that the amplitude of the combination tone at 2f1–f2 showed a variability of 10-20 dB depending on several parametric factors.

1.1 The frequency ratio of the primary tones (f2/f1)

The frequency ratio between the two primaries of 1.22 generates the highest DP from 1 to 4 kHz (61, 62). However, different ratio have been used, between 1.1 and 1.2 (63), and 1.25 (64).

Harris et al (62) reported that the most effective f2/f1 ratio was 1 to 1.22. However, they also reported an inverse relation between optimal f2/f1 ratio and the frequencies of the DPOAE. The optimal ratio for low frequency emissions was larger than for high frequency emissions which were 1.26 and 1.19 respectively. The optimal f2/f1 ratio also changes as a function of the intensity of the primary tones. As the intensity of the primary tones increases, the f2/f1 ratio used to elicit maximal DPOAE amplitude also increases.

1.2 The level of the primary tones (L1, L2)

The intensity of the stimulus used to generate the DPOAE may be low (<60 -70 dBSPL) or high (>70 dBSPL) and result in emissions with categorically different feature. When stimulus levels exceed 70 to 75 dBSPL, there is a high risk of encountering technical distortion in the instrumentation. This could lead to an invalid interpretation of test results. Additionally, high stimulus levels may be sampling more passive linear mechanisms in the cochlea that are less physiologically vulnerable to injury. Stimulus levels below approximately 60 dBSPL are more likely to be within the physiologically vulnerable range, but may not be of sufficient amplitude to produce distortion in all ears, especially those with peripheral cochlea damage (18). Reducing L2 from 6 to 15 dB below an L1 of 50 to 60 dBSPL is generally adequate to generate DPOAEs that are both detectable and vulnerable (60, 65).

1.3 The level difference between the two primary tones (L1-L2)

The intensity of the two primary tones, L1 and L2, that produce the maximum DPOAE amplitude is dependent on L1, where L1 is the intensity of f1 and L2 is the intensity of f2 (60). For high stimulus levels, the maximum DPOAE amplitude is generated when L1 equals L2 (66). For low stimulus levels, the optimum level is L1 greater than L2 by 15 dB (61,67). The finding of several recent studies determined that DPOAEs are maximal when L1 is greater than L2 10 to 15 dB (17,60,68).

Hauser & Probst (68) examined the influence of variations of primary-tone levels on amplitudes of DPOAEs at 2f1-f2 in 10 normal hearing subjects. They reported that setting L1 greater than L2 could improve the signal-to-noise of the DPOAE and therefore enhance detectability of the small amplitudes of DPOAEs.

DPOAEs amplitude in Normal hearing

The most common application of clinical tests with DPOAEs is for detecting an abnormal reduction of DPOAEs amplitude with a DP-gram. DP-gram is a graph of the amplitude of DPOAEs and noise level plotted against frequencies of f2, instead of the geometric mean of f1 and f2, reflecting the frequencies range of the conventional audiogram. (Figure 8).

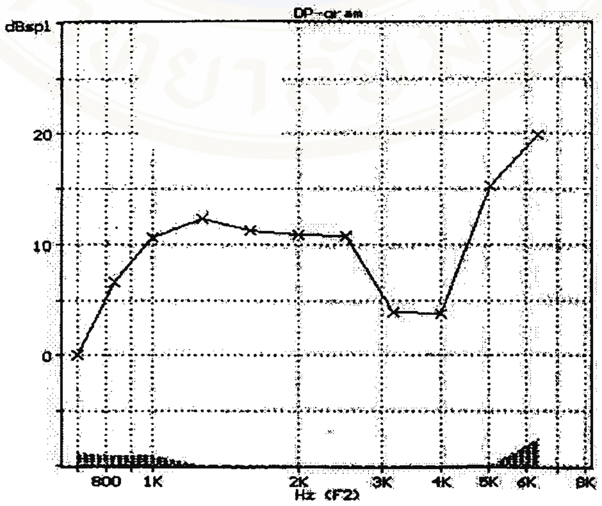

Figure 8 The example of a DP-gram shows the DPOAEs plotted in line curve above the noise floor (shaded area are noise level of +1SD and +2 SD)

Harris (18) found that the DPOAE were always detected when hearing thresholds at predetermined frequencies were better than 15 dBHL and absent attenuated when hearing loss more than 50 dBHL.

Probst and Hauser (17) studied the DPOAE amplitude from 46 subjects (77 ears) who had normal hearing; 25 subjects (36 ears) had near normal hearing; and 44 subjects (86 ears) exhibited varying degrees of SNHL caused by different pathologies. Their results showed the average DPOAEs amplitude for the normal and near normal group ranged from –0.6 to 9.4 dBSPL and –2 to 8.5 dBSPL, respectively. In SNHL group, the mean DPOAEs amplitudes were much lower than exceeded 10 dBSPL above the noise floor at only 1 and 1.5 kHz. However, the amplitudes and the frequency distribution of DPOAEs were dependent on the amount and shape of audiometric hearing losses in pathological ears. In normal hearing and near normal hearing, the DPOAE amplitudes was demonstrated in the frequency range of 1 to 4 kHz and a highly significant correlation between hearing thresholds and DPOAEs amplitude ($r = 0.42$ to 0.61, $p < .001$). The correlation did not reach significant levels ($r = 0.13$) at 6 kHz, and no correlation were found at either 0.5 kHz ($r = 0.037$) or 8 kHz ($r = 0.002$). In SNHL, no consistent correlation was detected between DPOAEs amplitudes and hearing thresholds.

Lonsbury-Martin et al (69) reported result DPOAEs amplitude from 94 normal hearing subjects (149 ears), aged from 15-64 years. The DPOAE were obtained using primary levels of 75 dBSPL at the geometric mean frequencies of the primaries from 0.8-8 kHz, with $f2/f1=1.21$. The mean DPOAE amplitudes peaked at about 1.2 kHz

(12.9±5.4 dBSPL) and 5.7 kHz (8.31±6.9 dBSPL) separated by a minimum at about 2.8 kHz (5.5±5.6 dBSPL).

Lonsbury-Martin et al (60) recorded DPOAEs amplitudes in 22 adult subjects (44 ears) with normal hearing at three primary-tone levels of 85, 75 and 65 dBSPL at primary tone frequencies that generated 2f1-f2 DPOAEs between 1 and 8 kHz. They suggested that the DPOAE amplitude peaked in two frequency ranges, with one maximum around 1.5 kHz and another peak at approximately 5.5 kHz, with a minimum at about 2 to 3 kHz between these two frequency region for all levels of stimulation. In the low-frequency region, DPOAEs amplitude reached a maximum of 17 dBSPL, whereas at high frequencies, DPOAEs attained a level of approximately 23 dBSPL. Spektor et al (70) studied the general shape of DP-gram in 7 normal hearing adults. They found that DP-gram was the presence of peak at 1.3 kHz (9.2 dBSPL) and 6 kHz (12.7 dBSPL) and trough in the 2 to 3 kHz region (4 dBSPL). The precise nature of the middle frequency decline in DPOAEs amplitude exhibited by normal hearing ears is unknown at this time. Probably, it is caused by an interaction of the resonance common to a particular individual's middle ear and cochlea. The lower frequency peak of the DP-gram is consistent with the frequency region associated with optimal middle ear conduction of acoustic signals. In contrast, the DPOAE maximum at the higher frequencies is unexpected because middle ear transmission attenuates OAEs in this frequency range.

DPOAEs amplitude in Sensorineural hearing loss

The association of cochlear damage resulting both in loss of hearing and in reduction in the amplitude of DPOAEs has been demonstrated by several investigators

(16, 60,71). In ears with SNHL, DPOAEs are generally reduced or eliminated only for the stimulus frequency regions coincident with the impaired region (16, 60). However, etiology of the hearing loss also appears to be a significant factor in determining the changes in DPOAEs.

Moulin et al (14) studied DPOAEs amplitude and hearing threshold in 81 hearing-impaired adults and 24 normal hearing. They found that, in hearing-impaired, DPOAEs were recorded with a hearing loss greater than 30 dBHL at low frequencies. However, high frequencies DPOAEs were recorded with a hearing loss greater than 45 dBHL (maximum of 60 dBSPL). Avan & Bonfils (72) reported that the DPOAE amplitude tended to decrease when hearing loss increased at 1 kHz and no subject had detectable DPOAE when 1 kHz hearing threshold was above 40 dB.

Harris (16) studied DPOAEs amplitude and pure tone behavioral thresholds in 20 ears with normal hearing and in 20 ears with high frequency sensorineural hearing loss. She found that DPOAEs amplitudes were reduced or absent in ears with high frequency sensorineural hearing loss. The difference occurred at frequencies above 1500 Hz. At 1000 kHz, DPOAEs amplitudes were within the same range for ears in both groups. At 4000 Hz, the majority of ears with elevated thresholds (> 25 dBHL) had DPOAEs that were below the mean amplitudes –2 standard deviations for the ears with normal hearing. However, several ears with thresholds of 50 to 60 dBHL had a DPOAEs judged present.

Oeken & Menj (73) studied DPOAEs in 59 subjects with normal hearing before and after definitive noise exposure (20 min of white noise at 90 dBHL). They measured DPOAEs changes during a 30 minute recovery period. They found a reduction of

DPOAEs amplitude averaged between 2 and 2.5 dBHL in the frequency range from 2 to 5 kHz.

DPOAEs and Pure-Tone results

The association of DPOAEs and pure tone results has been determined by examining large groups of persons with different pure tone threshold levels. Results from these investigations are summarized in Figure 9 (13, 15, 16 ,65 ,77 , 78). DPOAEs are related in a complex manner to hearing thresholds. This is due to a combination of both methodological and physiological factors. Section A represents that when DPOAEs for both high (70-70 dBSPL) and low levels (65-55 dBSPL) of stimulation are present across most frequencies at and above 1 kHz in 99 to 100% of ears. For frequencies above 4 kHz, this percentage decreases when stimuli are below 65 dBSPL (15). Section B represents that when hearing thresholds between 25 and 50 to 60 dBHL, DPOAEs amplitudes are generally reduced or the responses are absent. Detectable DPOAEs may be present for pure tone threshold levels as high as 50 to 60 dBHL, depending upon the stimulus levels used to produce them (15,16).Section C represents that when hearing thresholds above 50 to 60 dBHL DPOAEs are absent for both high level and low level stimulation.

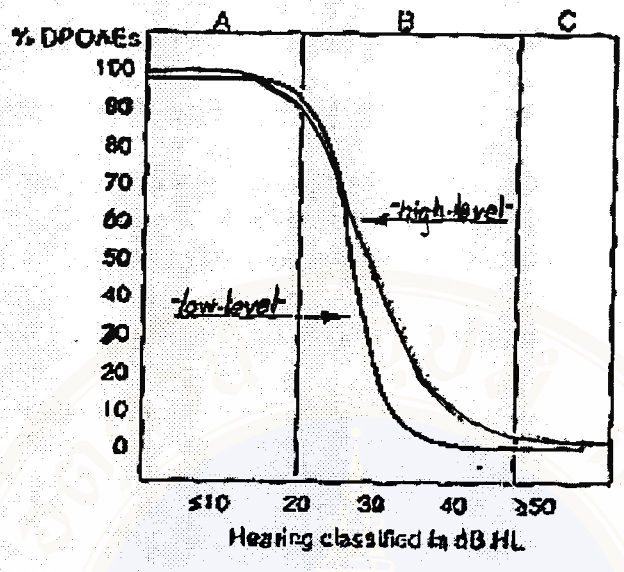

Figure 9 Schematic representation of the association of DPOAEs presence and average pure tone threshold levels. The two curves represent probabilities of obtaining a response for either low level or high level stimulation (18)

Interrelation between DPOAEs and CEOAEs

Because DPOAEs and CEOAEs are generated by the same process. Moreover, DPOAEs and CEOAEs were related to hearing threshold levels, an interrelation of the two emissions types would be expected. In general, when one type of OAE is present, the other will be also. The overall levels of the two responses are correlated. There are differences in the frequency range over which CEOAEs and DPOAEs may be measured effectively. CEOAEs are dominated by components in the mid-frequency range, and they are effective in sampling cochlear functioning in that range. DPOAEs can be measured over a broad range of frequencies, but they are present in the high frequencies more often than are CEOAEs. Gorga et al (13) have determined that, for the identification of hearing loss greater than 20 dBHL, both emissions performed well at 2 kHz. Click spectrum amplitudes were higher than DPOAE whereas the DPOAE amplitudes were higher than CEOAE amplitude above 4 kHz. Neither emission performs well at 0.5 kHz because the measurements are severely compromised by noise. If one emission type must be selected over another for clinical testing, then the purpose of the test should be considered. For the identification of hearing loss, CEOAEs may be preferable. Because the test is relatively quick (18). For monitoring purposes, DPOAEs may be preferable because they can be measured more easily in the high frequencies where ototoxic or noise-induced changes are more likely to occur (18).

Probst & Harris (75) investigated amplitude of CEOAEs and DPOAEs in 42 ears with normal hearing and 128 ears with varied degrees of SNHL. The results revealed that the amplitude ratio between DPOAEs and CEOAEs changed systematically with frequency. DPOAEs amplitude became larger with increasing frequency and CEOAEs amplitude became smaller. Therefore, CEOAEs showed the best coefficient found at 1 kHz, and DPOAEs showed the strongest correlations with the hearing threshold in the higher frequencies (35).

Probst & Harris (76) studied CEOAEs and DPOAEs amplitudes from 166 ears of individuals with and without hearing impairment. The results revealed a high correspondence between CEOAEs and DPOAEs (r= 0.78) and audiometric threshold levels at corresponding frequencies (DPOAEs, p= -0.84, CEOAEs , p= -0.77). The DPOAEs were present more often than were CEOAEs when hearing levels across frequency were greater than 30 dBHL

Clinical application

Clinical applications of DPOAEs depends on two factors. First, DPOAEs are an objective and noninvasive test. Second, DPOAEs is a frequency selectivity test, in particular high frequency activity (between 4 and 8 kHz). Its may provide a unique sensitivity to early stages of cochlear dysfunction, as many cochlear damage by external agents including noise and ototoxin or external factors such as viral or bacterial pathogens and genetically determined influences.

Kimberly et al (77) presented an application rule and suggested that DPOAEs measures could reliably categorize pure tone thresholds as normal or impaired in large populations with varied cochlear hearing status. They also recommened the DPOAE as an objective tool for mass hearing screening and for the evaluation of difficult to test populations.

CHAPTER III

MATERIALS AND METHODS

1. Subjects

A total of 27 male (45 ears) and 41female (75 ears) adults served as subjects. The age ranged between 18 and 40 years old. The subjects were separated into two groups

The first group consisted of 60 ears with normal hearing adults

The inclusion criteria were:

a) normal external ears and tympanic membranes by an otoscopic examination
b) normal hearing with a threshold of ≤ 25 dBHL at 250-8000 Hz (ANSI, 1969) by pure tone audiometry
c) type A tympanogram at 226 Hz probe tone and normal acoustic reflex threshold tested ipsilaterally at 500-2000 Hz and contralaterally at 500-4000 Hz

The second group consisted of 30 adults with sensorineural hearing loss of cochlea pathology characterized by ABR results

2. Instruments

The instruments used in this study were:

2.1 Otoscope

2.2 Audiometer- Madsen model OB 922 (ANSI, 1984)

2.3 Acoustic immittance instrument- Virtual 310 (ANSI, 1984)

2.4 Auditory brainstem response-Sierra version 2.1 (ANSI, 1984)

2.5 ILO 92 Otodynamic analyzer- Program ILO 292 DP Echoport version 5

3. Method

3.1 CEOAEs recordings

CEOAEs were recorded in a quiet room using ILO 292 DP Echoport Otodynamic analyzer (version 5). The stimulus consisted of a non-linear, non-filtered click of 80 μs duration stimulus level being adjusted in order to obtain a peak reception level of 80±3 dBSPL as recommended by Moulin et al (8). A rubber tip adapted to the size of the meatus was inserted on the probe (No. BPC 61042 B) in order to obtain a click stimulus waveform and power spectrum which were flat from 1 kHz to 5 kHz, with a decrease above and below this frequency range, as shown by Kemp et al. (17). The probe fitting stability was monitored during the recordings, and remained at 100 %. Click rate was 50 cps and post-stimulus analysis time was 20 ms. Two hundred and sixty sweeps were averaged and a bandpass of 500-4000 was employed.

3.2 DPOAEs recordings

The DPOAEs were recorded by a calibrated ear canal probe (No.BPC 61042B) containing two ports for the insert earphones and a sensitive low noise microphone system by ILO 292 DP Echoport Otodynamic Analyzer (version 5). The probe was sealed into the ear with a soft sponge ear tip.

The acoustic stimuli presented were two primary tones with a frequency ratio f2/f1 fixed at 1.22. The frequencies f1 and f2 and coincident DPOAEs 2f1-f2 and geometric mean frequencies were listed in Table 1. The interested DPs at 2f1-f2 were recorded throughout frequency sweep concerning the signal amplitude, the noise level at +1 and +2 standard deviation (SD), the signal-to-noise ratio (SNR) and the actual time spent or averaging at each frequency (f2). The level of primary tones used L1=65 and L2 =55 dBSPL because the amplitude of 2f1-f2 was highest when L1 is greater than L2 by 5 to 10 dBSPL difference (5,18,19,20,21).

Table 1. Frequencies for stimulation (f1 and f2), DPOAEs (2f1-f2) and the geometric frequency of f1 and f2

Frequency (Hz)			
GM	F1	F2	2F1-F2
500	574	696	452
750	684	830	538
1000	818	1001	635
1250	1038	1257	819
1500	1306	1587	1025
2000	1636	2002	1270
2500	2063	2515	1611
3000	2600	3174	2026
4000	3284	4004	2564
5000	4126	5042	3282
6000	5200	6348	4052

GM= Geometric means of f1 and f2

4. Procedures

In this study, three conditions of noise were recorded. First, the electronic noise was recorded by closing probe with finger. Second, the external noise were recorded by freely placing the probe outside at ears level. Finally, the canal noise resembled the noise level in the ear canal with good probe fitting.

During the measurements of the CEOAEs and DPOAEs, the subjects were placed in a reclining position in a comfortable chair inside a quiet room. The subjects were instructed to remain as quiet as possible during the test periods. Gross body, head and neck movements and swallowing were noted. In each measurement, with the proper fitting probe in place, the canal noise could be monitored to the satisfaction level below 45 dBSPL (17). The external noise was reduced to lower than 25 dBSPL after the ear canal had been sealed. The CEOAEs from both ears were recorded first (approximately 3 minutes per ear), then a complete DPOAE audiogram from one ear was obtained (during approximately 5 minutes) before beginning the testing on the second ear.

5. Criteria used to ensure a valid recording

In the present study, the criteria used to ensure a valid recording were based on those recommended by Kemp et al (39) for the ILO 88 Otodynamic analyzer using a nonlinear click stimulus.

CEOAEs: The criteria included

1. the response seen as a clear area above the noise floor and generally must be 3 dB higher than the noise level (22)

2. the presence of a continuous response of at least 200 width above the noise level in the spectral analysis panel (22)

3. presence of well defined, closely superimposed A & B tracing more than 70 % (12,18,22)

4. complete waveform by presence of an oscillatory response following a latency period of 3 msec and lasting period of time in the 20 msec time window

5. a click stimulus waveform without excessive oscillation (depent on proper probe fitting)

6. a click stimulus spectrum that was relatively flat, from 1-5 kHz (17)

DPOAEs – were considered as present when their amplitudes were more than 3 dB above the noise floor (mean + 2 SD) (13)

6. Data analysis

In this study, the following statistical methods SPSS for window were used to analyse the data.

1. Mean and standard deviation were used in the analysis of the CEOAEs response level (dBSPL), CEOAEs amplitude (dBSPL) and DPOAEs amplitude (dBSPL).

2. T-test was used to study the comparison between mean amplitude of CEOAEs (dBSPL) and DPOAEs (dBSPL) in normal hearing and hearing inpaired adult subjects.

3. Pearson's correlation coefficient was used to study the correlation between CEOAEs spectrum amplitude (dBSPL), DPOAEs amplitude (dBSPL) and pure tone audiometric threshold (dBHL) in normal hearing and hearing inpaired adult subjects.

CHAPTER IV

RESULTS

The purpose of the study was to investigate the relationships between CEOAEs and DPOAEs with a comparison to pure tone thresholds in the same group of normal hearing and hearing impaired adults. All results were presented as mean ± SD. Statistical evaluation of the data was performed with independent sample t-test for comparison between normal hearing and hearing impaired adults. Pearson's correlation coefficient was used to study the relationship between CEOAEs and DPOAEs amplitudes with pure tone audiometric thresholds in normal hearing and hearing impaired adults. CEOAEs and DPOAEs amplitudes were considered as present when their amplitudes were more than 3 dB above the noise floor (mean ± 2SD). The CEOAEs spectrum amplitudes of 1-4 kHz was analysed because click spectrum was limited to a region of 1-4 kHz. Because of a limited frequency spectrum of the click stimulus. For 500 Hz, the CEOAE measurement was interferred by the noise. The DPOAEs amplitudes of 1-6 kHz was analysed because the distortion product was able to be detected between 1-6 kHz and was difficult to test at frequencies 0.5 and 8 kHz.

Subjects consisted of two groups. The first group were 32 normal hearing adults (60 ears) which consisted of 7 males (12 ears) and 25 females (48 ears). The mean age was 26.73 years and the standard deviation was 3.58. The second group consisted of 36 adults (60 ears) with cochlear SNHL. There were 20 males (33 ears) and 16 females (27 ears). The mean age was 30.55 years and the standard deviation was 5.46. This group was subdivided into four groups based on the audiometric configurations between 0.25-8 kHz. Group A consisted of 27 ears (18males and 9 females) with 4-6 kHz audiometric notch. Pure tone thresholds (PTT) at 0.5 to 2 kHz and 8 kHz were equal to or better than 25 dBHL, only PTT at 4 to 6 kHz were greater than 25 dBHL. Group B consisted of 14 ears (9 males and 5 females) with high frequency sloping. PTT at 0.5 to 2 kHz equal to or better than 25 dBHL, and 4 to 8 kHz greater than 25 dBHL. Group C consisted of 6 ears (3 females) with low frequency sloping. PTT at 0.5 to 1 kHz greater than 25 dBHL, and 2 to 8 kHz equal to or better than 25 dBHL. Group D consisted of 13 ears (6 males and 7 females) with flat audiogram. PTT at 0.5 to 8 kHz greater than 25 dBHL. Audiometric configurations and means pure tone thresholds of all subjects in the second group were summarized in Table2. The data were collected in the Hearing Center at Mettapracharak hospital, Nakhonpratom province. The results were compared according to the research questions between normal hearing and hearing impaired adults.

Table 2 Summary of audiometric configurations and mean (SD) pure tone thresholds in dBHL at 0.25-8 kHz in normal hearing (NH) and hearing impaired adults (SNHL)

Frequency (kHz)	Group I	Group II (SNHL)			
	NH (n=60)	A (n=27)	B (n=14)	C (n=6)	D (n=13)
0.25	12.33 (5.24)	14.35 (6.08)	19.64 (5.70)	36.67 (2.58)	33.07 (3.84)
0.5	10.08 (4.91)	19.13 (8.48)	17.50 (5.89)	35.00 (5.47)	30.00 (9.61)
1	9.00 (5.19)	16.74 (5.96)	12.50 (6.35)	35.33 (8.91)	30.38 (8.66)
2	9.17 (4.89)	20.87 (9.94)	14.50 (5.50)	23.33 (2.58)	31.15 (9.39)
4	7.83 (6.34)	40.00 (8.77)	35.71 (8.78)	20.00 (3.16)	33.85 (3.63)
6	8.83 (6.26)	37.17 (7.50)	45.30 (7.23)	19.17 (5.85)	31.54 (7.97)
8	8.75 (7.04)	22.17 (8.09)	60.36 (7.95)	17.50 (6.12)	34.23 (5.71)

A = 4-6 kHz audiometric notch
C = low frequency sloping
B = high frequency sloping
D = flat audiogram

1. CEOAE response level (dBSPL) in normal hearing and hearing impaired adults

Table 3 showed the mean and standard deviation of CEOAE response level in normal hearing and hearing impaired adults. The mean and standard deviation of CEOAE response level in normal hearing was 11.87 dBSPL (SD=2.77) and in hearing impaired adult was 7.16 dBSPL (SD=4.13). The t-test showed a significant difference of CEOAE response level in normal hearing and hearing impaired adults at p-value < 0.05.

Table 3 Mean and standard deviation of CEOAE response level (dBSPL) in normal hearing (NH) and hearing impaired adults (SNHL)

CEOAE	NH (n=60)	SNHL(n=60)	t	p- value
Response level (dBSPL)	11.87 ± 2.77	7.16 ± 4.13	7.384**	0.000

**significant at p- value < 0.01

2. CEOAE spectrum amplitudes in normal hearing and hearing impaired adults

2.1 CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing and 4-6 kHz audiometric notch (group A)

From table 4, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz in normal hearing subjects were 15.18 (2.62), 17.68 (2.83), 13.80 (2.43), 12.02 (3.09) and 10.86 dBSPL (2.80), respectively. In group A, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz were 13.70 (4.43), 16.67 (2.31), 12.37 (1.83), 6.53 (1.68) and 5.18 dBSPL (1.13), respectively. The t-test showed a significant difference of CEOAE spectrum amplitudes at 2, 3 and 4 kHz between the subjects with normal hearing and those in group A at p-value < 0.01. There was no significant difference of CEOAE spectrum amplitudes at 1 and 1.5 kHz between the subjects with normal hearing and group A subjects.

Table 4 Mean and standard deviation of CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing (NH) and 4-6 kHz audiometric notch (group A)

Frequency (kHz)	NH (n=60)	Group A (n=27)	t	p- value
1	15.18 ± 2.62	13.70 ± 4.43	1.656	0.106
1.5	17.68 ± 2.83	16.67 ± 2.31	1.767	0.082
2	13.80 ± 2.43	12.37 ± 1.83	2.785**	0.007
3	12.02 ± 3.09	6.53 ± 1.68	8.726**	0.000
4	10.86 ± 2.80	5.18 ± 1.13	9.108**	0.000

** significant at p- value < 0.01

2.2 CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing and high frequency sloping (group B)

From table 5, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz in normal hearing subjects were 15.18 (2.62), 17.68 (2.83), 13.80 (2.43), 12.02 (3.09) and 10.86 dBSPL (2.80), respectively. In group B subjects, the means (SD) CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz was 14.08 (4.24), 15.95 (2.69), 12.37 (2.29), 7.8 (2.40) and 4.45 dBSPL (1.62), respectively. The t-test showed a significant difference of CEOAE spectrum amplitudes at 3 and 4 kHz between the subjects with normal hearing and those in group B at p-value < 0.01. There was no significant difference of CEOAE spectrum amplitudes at 1, 1.5, 2 kHz between the subjects with normal hearing and those in group B.

Table 5 Mean and standard deviation of CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing (NH) and high frequency sloping (group B)

Frequency (kHz)	NH (n=60)	Group B(n=13)	t	p- value
1	15.18 ± 2.62	14.08 ± 4.24	1.132	0.261
1.5	17.68 ± 2.83	15.95 ± 2.69	1.801	0.076
2	13.80 ± 2.43	12.37 ± 2.29	0.573	0.087
3	12.02 ± 3.09	7.85 ± 2.40	3.864**	0.000
4	10.86 ± 2.80	4.45 ± 1.62	3.198**	0.002

** significant at p- value < 0.01

2.3 CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing and low frequency sloping (group C)

From table 6, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz in normal hearing were 15.18 (2.62), 17.68 (2.83), 13.80 (2.43), 12.02 (3.09) and 10.86 dBSPL (2.80), respectively. In group C subjects, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz were 5.82 (1.03), 5.16 (1.15), 10.34 (1.70), 11.28 (1.04) and 10.66 dBSPL (4.26), respectively. The t-test showed a significant difference of CEOAE spectrum amplitudes at 1, 1.5 and 2 kHz between the subjects with normal hearing and those in group C at p-value < 0.01. There was no significant difference of CEOAE spectrum amplitudes at 3 and 4 kHz between the subjects with normal hearing and those in group C.

Table 6 Mean and standard deviation of CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing (NH) and low frequency sloping (group C)

Frequency (kHz)	NH (n=60)	Group C (n=6)	t	p- value
1	15.18 ± 2.62	5.82 ± 1.03	6.989**	0.000
1.5	17.68 ± 2.83	5.16 ± 1.15	8.446**	0.000
2	13.80 ± 2.43	10.34 ± 1.70	3.107**	0.003
3	12.02 ± 3.09	11.28 ± 1.04	1.267	0.223
4	10.86 ± 2.80	10.66 ± 4.26	0.149	0.882

** significant at p- value < 0.01

2.4 CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing and Flat audiogram (group D)

From table 7, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz in normal hearing were 15.18 (2.62), 17.68 (2.83), 13.80 (2.43), 12.02 (3.09) and 10.86 dBSPL (2.80), respectively. In group D subjects, the means (SD) of CEOAE spectrum amplitudes at 1, 1.5, 2, 3 and 4 kHz were 4.95 (2.05), 8.75 (3.71), 5.43 (2.49), 6.75 (3.09) and 7.36 dBSPL (2.63), respectively. The t-test showed a significant difference of CEOAE spectrum amplitudes at all frequencies between the subjects with normal hearing and those in group D at p-value < 0.01.

Table 7 Mean and standard deviation of CEOAE spectrum amplitudes (dBSPL) at 1-4 kHz in subjects with normal hearing and Flat audiogram (group D)

Frequency (kHz)	NH (n=60)	Group D (n=13)	t	p- value
1	15.18 ± 2.62	4.95 ± 2.05	10.611**	0.000
1.5	17.68 ± 2.83	8.75 ± 3.71	8.086**	0.000
2	13.80 ± 2.43	5.43 ± 2.49	9.125**	0.000
3	12.02 ± 3.09	6.75 ± 3.09	4.266**	0.000
4	10.86 ± 2.80	7.36 ± 2.63	3.519**	0.000

** significant at p- value < 0.01

3. DPOAE amplitudes in normal hearing and hearing impaired adults

3.1 DPOAE amplitudes (dBSPL) in subjects with normal hearing and group A

Table 8 showed the mean (SD) of DPOAE amplitudes at 1-6 kHz in subjects with normal hearing and those in group A. In the subjects with normal hearing, the means (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 16.81 (3.82), 21.26 (3.44), 19.52 (3.77), 17.30 (4.27), 20.99 (3.34) and 23.50 dBSPL (5.93), respectively. In group A subjects, the mean (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 15.27 (4.02), 19.90 (3.12), 18.11 (3.08), 11.96 (3.90), 11.73 (3.50) and 15.36 dBSPL (4.83), respectively. The t-test showed a significant difference of DPOAE amplitudes at 2, 3, 4 and 6 kHz between the subjects with normal hearing and those in group A at p-value < 0.01. There was no significant difference of DPOAE amplitudes at 1 and 1.5 kHz between the subjects with normal hearing and those in group A.

Table 8 Mean and standard deviation of DPOAE amplitude (dBSPL) at 1-6 kHz in subjects with normal hearing (NH) and group A

Frequency (kHz)	NH (n=60)	Group A(n=28)	t	p- value
1	16.81 ± 3.82	15.27 ± 4.02	1.722	0.089
1.5	21.26 ± 3.44	19.90 ± 3.12	1.770	0.080
2	19.52 ± 3.77	18.11 ± 3.08	4.350**	0.000
3	17.30 ± 4.27	11.96 ± 3.90	4.947**	0.000
4	20.99 ± 3.34	11.73 ± 3.50	5.947**	0.000
6	23.50 ± 5.93	15.36 ± 4.83	5.243**	0.000

* significant at p- value < 0.05; ** significant at p- value < 0.01

3.2 DPOAE amplitudes (dBSPL) in subjects with normal hearing and group B

Table 9 showed the mean and standard deviation of DPOAE amplitudes at 1-6 kHz in the subjects with normal hearing and those in group B. In subjects with normal hearing, the means (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 16.81 (3.82), 21.26 (3.44), 20.34 (4.60), 17.30 (4.27), 18.91 (4.87) and 23.50 dBSPL (5.93), respectively. In group B subjects, the means (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 16.36 (4.95), 21.19 (3.23), 19.00 (4.11), 15.84 (6.86), 14.66 (2.15) and 10.17 dBSPL (4.95), respectively. The t-test showed a significant difference of DPOAE amplitudes at 4 and 6 kHz between the subjects with normal hearing and those in group B at p-value< 0.01. There was no significant difference of DPOAE amplitudes at 1, 1.5, 2 and 3 kHz between the subjects with normal hearing and those in group B.

Table 9 Mean and standard deviation of DPOAE amplitudes (dBSPL) at 1-6 kHz in subjects with normal hearing (NH) and group B

Frequency (kHz)	NH(n=60)	group B (n=13)	t	p- value
1	16.81 ± 3.82	16.36 ± 4.95	0.330	0.742
1.5	21.26 ± 3.44	21.19 ± 3.23	0.056	0.956
2	20.34 ± 4.60	19.00 ± 4.11	0.867	0.389
3	17.30 ± 4.27	15.84 ± 6.86	0.620	0.551
4	18.91 ± 4.87	14.66 ± 2.15	4.562**	0.000
6	23.50 ± 5.93	10.17 ± 4.95	5.706**	0.000

** significant at p- value < 0.01

3.3 DPOAE amplitudes (dBSPL) in subjects with normal hearing and group C

Table 10 showed the mean and standard deviation of DPOAE amplitudes at 1-6 kHz in subjects with normal hearing and those in group C. In the subjects with normal hearing, the mean (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were16.81 (3.82), 21.26 (3.44), 20.34 (4.60), 17.30 (4.27), 18.91 (4.87) and 23.50 dBSPL (5.93), respectively. In group C subjects, the mean (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 6.2 (1.73), 12.92 (1.30), 17.35 (6.57), 16.13 (0.81), 15.11 (6.49) and 19.51 dBSPL (7.90), respectively. The t-test showed a significant difference of DPOAE amplitudes at 1, 1.5 kHz between the subjects with normal hearing and those in group C at p-value < 0.01. There was no significant difference of DPOAE amplitudes at 2, 3, 4 and 6 kHz between the subjects with normal hearing and those in group C.

Table 10 Mean and standard deviation of DPOAE amplitudes (dBSPL) at 1-6 kHz in subjects with normal hearing (NH) and group C

Frequency (kHz)	NH(n=60)	group C (n=6)	t	p- value
1	16.81 ± 3.82	6.2 ± 1.73	4.763**	0.000
1.5	21.26 ± 3.44	12.92 ± 1.30	4.792**	0.000
2	20.34 ± 4.60	17.35 ± 6.57	1.231	0.223
3	17.30 ± 4.27	16.13 ± 0.81	0.666	0.077
4	18.91 ± 4.87	15.11 ± 6.49	1.440	0.155
6	23.50 ± 5.93	19.51 ± 7.90	1.369	0.176

** significant at p- value < 0.01

3.4 DPOAE amplitudes (dBSPL) in subjects with normal hearing and group D

Table 11 showed the mean and standard deviation of DPOAE amplitudes at 1-6 kHz in subjects with normal hearing and those in group D. In subjects with normal hearing, the mean (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 16.81 (3.82), 21.26 (3.44), 20.34 (4.60), 17.30 (4.27), 18.91 (4.87) and 23.50 dBSPL (5.93), respectively. In group D subjects, the mean (SD) of DPOAE amplitudes at 1, 1.5, 2, 3, 4 and 6 kHz were 8.64 (6.05), 14.12 (4.05), 13.22 (2.66), 14.71 (4.61), 17.98 (4.36) and 21.75 dBSPL (4.55), respectively. The t-test showed a significant difference of DPOAE amplitudes at 1, 1.5 and 2 kHz between the subjects with normal hearing and those in group D at p-value < 0.01. There was no significant difference of DPOAE amplitudes at 3, 4 and 6 kHz between the subjects with normal hearing and those in group D.

Table 11 Mean and standard deviation of DPOAE amplitudes (dBSPL) at 1-6 kHz in subjects with normal hearing (NH) and group D

Frequency (kHz)	NH(n=60)	group D (n=13)	t	p- value
1	16.81 ± 3.82	8.64 ± 6.05	5.717**	0.000
1.5	21.26 ± 3.44	14.12 ± 4.05	5.924**	0.000
2	20.34 ± 4.60	13.22 ± 2.66	4.520**	0.000
3	17.30 ± 4.27	14.71 ± 4.61	1.825	0.072
4	18.91 ± 4.87	17.98 ± 4.36	0.610	0.544
6	23.50 ± 5.93	21.75 ± 4.55	0.924	0.359

** significant at p- value < 0.01

4. CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in normal hearing adults

Table 12 showed the correlation coefficient between CEOAE amplitudes and DPOAE amplitudes at 1-4 kHz in normal hearing adults. The correlation coefficient (r) between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz were 0.498, 0.349, 0.525, 0.287 and 0.323 respectively. The Pearson's product moment showed a significant correlation between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2 kHz at p-value < 0.01 and 3, 4 kHz at p-value < 0.05.

Table 12 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in normal hearing adults

Frequency (kHz)	r	p- value
1	0.498^{**}	0.000
1.5	0.349^{**}	0.006
2	0.525^{**}	0.000
3	0.287^{*}	0.026
4	0.323^{*}	0.012

* significant at p- value < 0.05; ** significant at p- value < 0.01

5. CEOAE amplitudes and DPOAE amplitudes in the same subjects

5.1 CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group A subjects

Table 13 showed the correlation coefficient between CEOAE amplitudes and DPOAE amplitudes at 1-4 kHz in group A subjects. The correlation coefficient (r) between CEOAE spectrum amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz were 0.509, 0.515, 0.586, 0.661 and 0.766, respectively. The Pearson's product moment showed a significant positive correlation between CEOAE amplitudes and DPOAE amplitudes in group A subjects at all frequencies, and the strongest correlation was 4 kHz.

Table 13 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group A subjects

Frequency (kHz)	r	p- value
1	0.509^{**}	0.006
1.5	0.515^{**}	0.008
2	0.586^{**}	0.004
3	0.661^{*}	0.037
4	0.766^{**}	0.002

** significant at p- value < 0.01

5.2 CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group B subjects

Table 14 showed the correlation coefficient between CEOAE amplitudes and DPOAE amplitudes at 1-4 kHz in group B subjects. The correlation coefficient (r) between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz were 0.911, 0.883, 0.934, 0.896 and 0.634, respectively. The Pearson's product moment showed a significant positive correlation between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2 and 3 kHz in subjects with high frequency loss at p-value < 0.01 and 4 kHz at p-value < 0.05.

Table 14 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group C subjects

Frequency (kHz)	r	p- value
1	0.911**	0.000
1.5	0.883**	0.001
2	0.934**	0.000
3	0.896**	0.000
4	0.634	0.049

* significant at p- value < 0.05; ** significant at p- value < 0.01

5.3 CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group C subjects

Table 15 showed the correlation coefficient between CEOAE amplitudes and DPOAE amplitudes at 1-4 kHz in group C subjects. The correlation coefficient (r) between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz were 0.851, 0.998, 0.992, 0.931 and 0.962, respectively. The Pearson's product moment showed a significant correlation between CEOAE amplitudes and DPOAE amplitudes at 1.5, 2, 3 and 4 kHz at p-value < 0.01 and 1 kHz at p-value < 0.05 in group C subjects.

Table 15 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group C subjects

Frequency (kHz)	r	p- value
1	0.851*	0.031
1.5	0.998**	0.002
2	0.992**	0.008
3	0.931**	0.007
4	0.962**	0.002

** significant at p- value < 0.01

5.4 CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group D subjects

Table 16 showed the correlation coefficient between CEOAE amplitudes and DPOAE amplitudes at 1-4 kHz in group D subjects. The correlation coefficient (r) between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz were 0.298, 0.103, 0.175, 0.420 and 0.097, respectively. There was no correlation between CEOAE amplitudes and DPOAE amplitudes at 1, 1.5, 2, 3 and 4 kHz.

Table 16 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and DPOAE amplitudes (dBSPL) in group D subjects

Frequency (kHz)	r	p- value
1	0.298	0.473
1.5	0.103	0.808
2	0.175	0.708
3	0.366	0.420
4	0.097	0.765

6. CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds at 1-4 kHz in normal hearing adults

Table 17 showed the correlation coefficient between CEOAE spectrum amplitudes and pure tone thresholds at 1-4 kHz in normal hearing adults. The correlation coefficient (r) of CEOAE amplitude and pure tone thresholds at 1, 2 and 4 kHz in normal hearing adults was -0.464, -0.537 and –0.367, respectively. The Pearson's product moment showed a significant negative correlation between CEOAE amplitudes and pure tone thresholds at 1, 2, 4 kHz in normal hearing adults at p-value < 0.01. CEOAE spectrum amplitudes decreased significantly as pure tone thresholds increased.

Table 17 Pearson's correlation coefficient (r) between CEOAE amplitudes (dBSPL) and pure tone thresholds (dBHL) at 1-4 kHz in normal hearing adults

Frequency (kHz)	r	p- value
1	-0.464**	0.000
2	-0.537**	0.000
4	-0.367**	0.004

** significant at p-value < 0.01

7. CEOAE spectrum amplitudes and pure tone thresholds in hearing impaired subjects

7.1 CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds at 1-4 kHz in group A subjects

Table 18 showed the correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1-4 kHz in group A subjects. The correlation coefficient (r) of CEOAE spectrum amplitudes and pure tone thresholds at 1, 2 and 4 kHz in group A subjects were -0.826, -0.664 and -0.862, respectively. The Pearson's product moment showed a significant negative correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1, 2 and strong negative correlation at 4 kHz in group A subjects.

Table 18 Pearson's correlation coefficient (r) between CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds (dBHL) in group A subjects

Frequency (kHz)	r	p- value
1	-0.826**	0.000
2	-0.614**	0.000
4	-0.862**	0.000

** significant at p-value < 0.01

7.2 CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds in group B subjects

Table 19 showed the correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1-4 kHz in group B subjects. The correlation coefficient (r) of CEOAE spectrum amplitudes and pure tone thresholds at 1, 2 and 4 kHz in group B subjects were -0.801, -0.708 and -0.718, respectively. The Pearson's product moment showed a significant negative correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1 kHz at p-value < 0.01 and 2, 4 kHz at p-value < 0.05 in group B subjects.

Table 19 Pearson's correlation coefficient (r) between CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds (dBHL) in group B subjects

Frequency (kHz)	r	p- value
1	-0.801^{**}	0.005
2	-0.708^{*}	0.022
4	-0.718^{*}	0.019

* significant at p-value < 0.05; ** significant at p-value < 0.01

7.3 CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds in group C subjects

Table 20 showed the correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1-4 kHz in group C subjects. The correlation coefficient (r) of CEOAE spectrum amplitudes and pure tone thresholds at 1, 2 and 4 kHz in group C subjects were -0.872, -0.075 and -0.011, respectively. The Pearson's product moment showed a significant negative correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1 kHz at p-value < 0.05 in group C subjects. No significant correlation was found at 2 and 4 kHz

Table 20 Pearson's correlation coefficient (r) between CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds (dBHL) in group C subjects

Frequency (kHz)	r	p- value
1	-0.872*	0.024
2	-0.075	0.859
4	-0.111	0.776

* significant at p-value < 0.05

7.4 CEOAE spectrum amplitudes (dBSPL) and pure tone thresholds in group D subjects

Table 21 showed the correlation between CEOAE spectrum amplitudes and pure tone thresholds at 1-4 kHz in group D subjects. The correlation coefficient (r) of CEOAE spectrum amplitudes and pure tone thresholds at 1, 2 and 4 kHz in group D subjects were -0.364, -0.671 and -0.718, respectively. No significant correlation was found between CEOAE spectrum amplitudes and pure tone thresholds all frequencies in group D subjects.

Table 21 Pearson's correlation coefficient (r) between CEOAE spectrum amplitudes and pure tone thresholds in group D subjects

Frequency (kHz)	r	p- value
1	-0.364	0.375
2	-0.671	0.215
4	-0.023	0.966

8. DPOAE amplitudes (dBSPL) with pure tone thresholds in normal hearing adults

Table 22 showed the correlation between DPOAE amplitudes at 1-6 kHz with pure tone thresholds in normal hearing adults. The correlation coefficient (r) between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz was -0.323, -0.409, -0.449 and -0.355, respectively. The Pearson's product moment showed a significant negative correlation between DPOAE amplitudes and pure tone thresholds at 2, 4 and 6 kHz at p-value < 0.01 and 1 kHz at p-value < 0.05 in normal hearing adults.

Table 22 Pearson's correlation coefficient (r) between DPOAE amplitudes (dBSPL) with pure tone thresholds (dBHL) in normal hearing adults

Frequency (kHz)	DPOAE	
	r	p- value
1	-0.323*	0.012
2	-0.409**	0.001
4	-0.449**	0.000
6	-0.355**	0.005

* significant at p- value < 0.05; ** significant at p- value < 0.01

9. DPOAE amplitudes with pure tone thresholds in hearing impaired subjects

9.1 DPOAE amplitudes (dBSPL) with pure tone thresholds in group A subjects

Table 23 showed the correlation coefficient between DPOAE amplitudes at 1-6 kHz with pure tone thresholds in group A subjects. The correlation coefficient (r) between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz were -0.499, -0.417, -0.718 and -0.684, respectively. The Pearson's product moment showed a significant negative correlation between DPOAE amplitudes and pure tone thresholds at 1, 4, 6 kHz at p-value < 0.01 and 2 kHz at p-value < 0.05 in group A subjects.

Table 23 Pearson's correlation coefficient between DPOAE amplitudes (dBSPL) and pure tone thresholds (dBHL) in group A subjects.

Frequency (kHz)	DPOAE	
	r	p- value
1	-0.499^{**}	0.007
2	-0.417^{*}	0.027
4	-0.718^{**}	0.000
6	-0.684^{**}	0.000

* significant at p- value < 0.05; ** significant at p- value < 0.01

9.2 DPOAE amplitudes (dBSPL) with pure tone thresholds in group B subjects

Table 24 showed the correlation coefficient between DPOAE amplitudes at 1-6 kHz with pure tone thresholds in group B subjects. The correlation coefficient (r) between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz was -0.633, -0.726, -0.810 and -0.827, respectively. The Pearson's product moment showed a significant negative correlation between DPOAE amplitudes and pure tone thresholds at 4 kHz at p-value < 0.01 and 1, 2, 6 kHz at p-value < 0.05 in group B subjects.

Table 24 Pearson's correlation coefficient (r) between DPOAE amplitudes (dBSPL) and pure tone thresholds (dBHL) in group B subjects

Frequency (kHz)	DPOAE	
	r	p- value
1	-0.633*	0.050
2	-0.726*	0.017
4	-0.810**	0.004
6	-0.827*	0.022

* significant at p- value < 0.05; ** significant at p- value < 0.01

9.3 DPOAE amplitudes (dBSPL) with pure tone thresholds in group C subjects

Table 25 showed the correlation coefficient between DPOAE amplitudes at 1-6 kHz with pure tone thresholds in group C subjects. The correlation coefficient (r) between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz were -0.874, -0.992, -0.058 and -0.800, respectively. The Pearson's product moment showed a significant negative correlation between DPOAE amplitudes and pure tone thresholds at1 kHz at p-value < 0.05 in group C subjects. There was no significant correlation between DPOAE amplitudes and pure tone thresholds at 2, 4 and 6 kHz in group C subjects.

Table 25 Pearson's correlation coefficient between DPOAE amplitudes (dBSPL) and pure tone thresholds (dBHL) in group C subjects

Frequency (kHz)	DPOAE	
	r	p- value
1	-0.874*	0.023
2	-0.588	0.297
4	-0.058	0.912
6	-0.800	0.056

** significant at p- value < 0.01

9.4 DPOAE amplitudes (dBSPL) with pure tone thresholds in group D subjects

Table 26 showed the correlation coefficient between DPOAE amplitudes at 1-6 kHz with pure tone thresholds in group D subjects. The correlation coefficient between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz was -0.509, -0.316, -0.097 and -0.260, respectively. There was no significant correlation between DPOAE amplitudes and pure tone thresholds at 1, 2, 4 and 6 kHz in group D subjects.

Table 26 Pearson's correlation coefficient between DPOAE amplitudes (dBSPL) and pure tone thresholds (dBHL) in group D subjects

Frequency (kHz)	DPOAE	
	r	p- value
1	-0.509	0.133
2	-0.316	0.407
4	-0.097	0.765
6	-0.260	0.439

CHAPTER V

DISCUSSION

This study was conducted to investigate the data of CEOAEs and DPOAEs in 60 ears with normal hearing and 60 ears with hearing impaired adults.The characteristics of the CEOAEs and DPOAEs in ears with hearing impaired significantly differed from those of the normal hearing ears, according to all parameters tested in the present study.

1. The CEOAEs response level in normal hearing and hearing impaired adult

The result in table 3, the CEOAEs response level in normal hearing subjects were significantly higher than those in hearing impaired subjects. These findings agreed with those from Glattke et al (47), Qiu et al (50) and Attias et al (56). They found that, the CEOAEs response level tended to decrease or absent as the hearing threshold increased. In hearing impaired, the CEOAEs response level decreased with roughly approximately 10 dBSPL decrement for a 10 dBHL loss of hearing (45).

2. The CEOAEs spectrum amplitudes

2.1 The CEOAEs spectrum amplitudes between normal hearing and 4-6 kHz audiometric notch (group A)

According to the CEOAEs spectrum between 1 and 4 kHz, the normal hearing groups showed maximum amplitudes between 1 and 1.5 kHz. These findings agreed with those from Bonfils et al (9), Vedantam & Musiek (45), Probst et al (51), Kemp (80) and Harris & Probst (54).The CEOAEs spectrum amplitudes decreased above 4 kHz because of a limited frequency spectrum of the click stimulus also, the maximum amplitude between 1-1.5 kHz was due to maximum middle ear transduction properties. From table 4, the mean CEOAEs spectrum amplitudes at 2, 3 and 4 kHz in group A were significantly lower than those in normal hearing subjects. The results of this study agreed with that of Hotz et al (54). They revealed significant changes in CEOAEs spectrum amplitudes in the frequency range from 2 to 4 kHz, whereas changes in the frequency range from 0.5 to 2 kHz were not significant. These differential frequency effects were consistent with what might be expected from cochlear damage due to the noise (54). In group A, a notch at 4-6 kHz was a result of OHCs damage due to noise exposure. Histological analyses of human ears exposed to noise have clearly shown more hair cell degeneration at basal cochlear sites, the 3-6 kHz frequency range (81, 82). Apart from the 4-6 kHz notch, the CEOAEs amplitude at 2 and 3 kHz were also lower than normal hearing. This probably was due to upward damage of some OHCs in the region of 2 and 3 kHz by the loud noise (83, 84).

2.2 The CEOAEs spectrum amplitudes between subjects with normal hearing and high frequency sloping (group B)

In table 5, the mean CEOAEs spectrum amplitudes at 3 and 4 kHz in group B subjects were significantly lower than those in normal hearing subjects. In the lower to middle frequency ranges, where the hearing thresholds were within normal limit, the ears in group B showed lower CEOAEs amplitudes than those in normal hearing.

These findings agreed with those from Bonfils & Uziel (12) and Hauzer et al (52). In the high frequency loss, the OHCs loss usually begins in the basal turn of the cochlea and continues toward in the apical direction. Consistent with this histological finding, the three rows of OHCs were destructed (inner rows of OHCs were initially) while the IHCs were still intact. This may imply that the number of OHCs at aparticular region may have a correlation with the amount of the CEOAEs amplitudes and hearing threshold at that critical frequency.

2.3 The CEOAEs spectrum amplitudes between subjects with normal hearing and low frequency sloping (group C)

The CEOAEs spectrum amplitude between subjects with normal hearing and group C subjects were shown in table 6. The CEOAEs spectrum amplitude at 1, 1.5 and 2 kHz in normal hearing were significantly higher than those in group C. The results revealed that CEOAE responses could be measured at all low frequency sloping despite the presence of average hearing losses exceeding 25 dBHL. Similar findings were reported by Lind & Randa (58). They found that CEOAE responses could be measured in most of the patients with low frequency sloping accompanied by preserved hearing at 2 and 4 kHz. In the high frequency, the hearing thresholds were better than 20 dBHL. The ears in group C showed CEOAEs amplitudes which were within normal limit.

2.4 The CEOAEs spectrum amplitudes between subjects with normal hearing and flat audiogram (group D)

There were no reports comparing CEOAEs spectrum amplitudes between normal hearing and group D subjects. In table 7, the means CEOAEs amplitudes at 1-4 kHz in group D subjects were significantly lower than those in normal hearing subjects. CEOAEs could be found in all normal hearing ears when pure tone thresholds was better than 20 dBHL, and absent when pure tone thresholds were greater than 40 dBHL (18). According to the gray zone of OAEs response with the hearing thresholds between 25 to 35 dBHL, CEOAEs may be present but are generally reduced in amplitude of as compare to the findings from ears with normal hearing (18). The hearing thresholds at all frequencies in ears of group D subjects were between 25 to 40 dBHL, thus, the lower CEOAEs amplitudes should be expected in all frequencies.

3. The DPOAEs amplitudes

3.1 The DPOAEs amplitudes between normal hearing and group A

According to the DPOAEs spectrum, the best DPOAEs response ranged between 1 and 6 kHz (17). From the results in table 8, the DPOAEs amplitudes peaked in two frequencies range, with one maximum around 1.5 kHz (21.26 ± 3.44) and another peak at approximately 6 kHz (23.50 ± 5.93), with a minimum at about 2 to 3 kHz (19.52 ± 3.77 and 17.30 ± 4.27). These findings agreed with those from Moulin et al (8), Kemp (80), Lonbury-Martin et al (60), Lonbury-Martin et al (69) and Spektor et al (70). The precise nature of the middle frequency decline in DPOAEs amplitude exhibited by normal hearing ears is unknown at this time. Probably, it is caused by an interaction of the resonance common to a particular individual's middle ear and the cochlea. The lower frequency peak of the DP-gram is consistent with the frequency region associated with optimal middle ear conduction of acoustic signals. In contrast, the DPOAE maximum at the higher frequencies is unexpected because middle ear transmission attenuates OAEs in this frequency range.

In table 8, the mean DPOAEs amplitudes at 2, 3, 4 and 6 kHz in group A subjects were significantly lower than those in normal hearing subjects. The results of this study agreed with Oeken & Menj (73) and Attias et al (74). These finding suggested a reduction of DPOAEs amplitudes in the frequency from 2 to 5 kHz. The reduction of DPOAEs amplitudes was probably due to the damage of the cochlea between 8 and 10 mm, which may cause a loss of OHCs with an alternation of their anatomic changed from the basal toward the apex (82).

3.2 The DPOAEs amplitudes between normal hearing and group B

In table 9, the means DPOAEs amplitudes at 4 and 6 kHz in group B subjects were significantly lower than in normal hearing. The results of this study agreed with that of Harris (16). She found a significant difference between normal hearing and high frequency loss from frequencies above 3000 Hz. In group B, the presence of an alternation in cochlea was possibly due to a loss of the OHCs in the base of cochlea. The estimateed hearing thresholds at 3 kHz in ears of group B subjects were slightly greater than 25 dBHL, thus, the CEOAEs amplitudes were significantly lower than those in normal hearing groups. While DPOAEs amplitudes were reduced without any significant difference. This finding showed the robustness of the DPOAEs over the CEOAEs in measuring the ears with hearing threshold in gray zone.

3.3 The DPOAEs amplitudes between normal hearing and group C

From the results in table 10, the mean DPOAEs amplitudes at 1 and 1.5 kHz in group C subjects were significantly lower than those in normal hearing. These findings agreed with those from Spektor et al (70). They found that the DPOAEs amplitudes were decreased in the low frequency range up to approximately 1500 Hz, and fell within a normal range at high frequency. Detection of hearing loss for low frequencies using DPOAEs appear to be difficult, in part due to higher background noise in the low frequency. DPOAEs were diminished or absent when the primary tone frequencies originated from a damage cochlear area (14). Thus, lower DPOAEs amplitudes also indicated poorer hair cell function in group C subjects. The hearing thresholds at 2 kHz in ears of group C subjects were slightly greater than 25 dBHL, thus, the CEOAEs amplitudes were significantly lower than those in normal hearing groups. While DPOAEs amplitudes were reduced without significant difference. This finding showed the robustness of the DPOAEs over the CEOAEs in measuring the ears with hearing threshold in gray zone.

3.4 The DPOAEs amplitudes between normal hearing and group D

There were no reports of DPOAEs amplitudes comparison between normal hearing and group D subjects were found. In table 11, the mean DPOAEs amplitudes at 1, 1.5 and 2 kHz were significantly lower than those in normal hearing. Zurek et al

(85) concluded that DPOAEs were sensitive indicators of cochlear damage and that DPOAEs levels were permanently reduced when the areas corresponding to the primary tones were damaged. The good correlation between DPOAEs and hearing thresholds was reported to be consistent when the hearing loss less than 20 dBHL or greater than 50 dBHL. However, the agreement between DPOAEs and hearing thresholds was found to be varied for hearing loss in the range of 20 to 50 dBHL (18). The estimateed hearing thresholds at 3 and 4 kHz in ears of group D subjects were slightly greater than 25 dBHL, thus, the CEOAEs amplitudes were significantly lower than those in normal hearing groups. While DPOAEs amplitudes were reduced without significant difference. This finding showed the robustness of the DPOAEs over the CEOAEs in measuring the ears with hearing threshold in gray zone.

4. The relationship between CEOAEs and DPOAEs amplitudes in normal hearing subjects

The result in table 12 showed the significant positive relationship between CEOAEs and DPOAEs amplitudes at 1, 1.5, 2, 3 and 4 kHz from the same ear. The CEOAEs and DPOAEs amplitudes of the five frequencies were correlated; the 1, 1.5 and 2 kHz correlation were higher than the 3 and 4 kHz, probably due to the click stimulus spectrum limited to the frequencies below 4 kHz. However, DPOAEs amplitudes were about slightly higher at 4 kHz than at either 1, 1.5 or 2 kHz. These findings suggested that some common mechanism be involved in the generation of CEOAEs and DPOAEs in the human cochlea. Even though the two types of OAEs exhibit some differences, they are both believed to arise from nonlinear active biomechanical properties of OHCs (76, 77).

5. The relationship between CEOAEs and DPOAEs amplitudes in hearing impaired subjects

The result in table 13, 14 and 15 showed the significant positive relationship between CEOAEs and DPOAEs amplitudes at 1, 1.5, 2, 3 and 4 kHz in hearing impaired subjects, group A, B and C, respectively. Many researcheres agreed that DPOAEs and CEOAEs occurred from the same active process in the cochlea (35,76,77,78). DPOAEs were diminished or absent when the primary tones corresponded to the region of hearing impairment (45,70,74,75). Other reports showed that the CEOAEs spectrum amplitudes were decreased in the 2-4 kHz frequency region for subjects with hearing loss in this frequency region (2,39). This implied that a correlation between the two types of OAEs could be found in impaired ears.

From the result in group D (table 15), there was no relationship found between CEOAEs and DPOAEs amplitudes. The OAEs amplitudes were evaluated at frequencies with PTT better than 30-35 dBHL for CEOAEs and 60 dBHL for DPOAEs (10). In this study, nine ears in group D having PTT less than 35 dBHL and four ears having PTT more than 35 dBHL. Thus, in ears with PTT more than 35 dBHL, CEOAEs were immeasurable but DPOAEs were reduced but still measurable.

6. The relationship between CEOAEs spectrum amplitudes and pure tone threshold in normal hearing adults

Table 17, showed the negative relationship between CEOAEs spectrum amplitudes and PTT at 1, 2 and 4 kHz. These findings agreed with those from Lonsbury- Martin et al (6), Cope & Lutman (42) and Hotz et al (54). The contour of the CEOAEs spectrum amplitudes usually approximated the PTT at the same or close frequencies. The CEOAEs and PTT share partly features of a common mechanism, the CEOAEs amplitudes and PTT was inversely related. When PTT was better than 20 dBHL at all frequencies, CEOAEs were present in 99 % of ears. When all PTT from 0.25-8 kHz were greater than 40 dBHL, CEOAEs were absent in 100% of ears. In subjects with normal hearing levels between 25-35 dBHL, the presence of CEOAEs varied between 20-80 % (18). However, normal hearing levels were also present in those who had healthy cochlear function.

7. The relationship between CEOAEs spectrum amplitudes and pure tone threshold in hearing impaired adults

The results in group A and B (table18, 19) showed the negative relationship between CEOAEs amplitudes and PTT. These findings agreed with those from Harris & Probst (18) and Probst & Harris (76). The CEOAEs amplitudes and PTT were inversely related, that is the CEOAEs amplitudes decreased as PTT increased. In this study, the means PTT at 1 and 2 kHz in group A and B were better than 20 dBHL, thus, CEOAEs amplitudes were present. However, at 4 kHz PTT from both groups were greater than 35 dBHL. Therefore, the CEOAEs were absent.

The results in group C and D (table 20 and 21) showed no relationship between CEOAEs amplitudes and PTT in group C (except 1 kHz) and group D, because PTT in these groups fell in the range of 25-35 dBHL, thus, the presence of CEOAEs were generally reduced or absent. These findings suggested that in ears with hearing impaired, good correlation between CEOAEs spectrum amplitudes and PTT when the hearing loss was less than 20 dBHL or greater than 35 dBHL. However, the agreement between the CEOAEs amplitudes and PTT was found to be poorer for hearing loss in the range of 25 to 35 dBHL. Moreover, differential pathology and etiology of the hearing loss also appeared to be a significant factor in determined the change in CEOAEs (16).

8. The relationship between DPOAEs amplitudes and pure tone threshold in normal hearing adults

Table 22 showed the negative relationship between DPOAEs amplitudes and PTT at 1, 2, 4 and 6 kHz. These findings agreed with those from Probst et al (76) and Avan et al (82). The DPOAEs amplitudes were correlated with PTT at frequency close to f2. When the low levels of stimulation were used, DPOAEs amplitudes were absent above hearing levels of approximately 50 to 60 dBHL (18). When PTT was better than 20 dBHL, DPOAEs amplitudes were present (18). In this study, DPOAEs stimuli (f1, f2) were low level pure tones (L1=65, L2=55 dBSPL).

9. The relationship between DPOAEs amplitudes and pure tone threshold in hearing impaired adults

The results in group A and B (table 23, 24) showed negative relationship between DPOAEs amplitudes and PTT. These findings agreed with those from Harris & Probst (18) and Probst & Harris (76). The DPOAEs amplitudes and PTT was inversely related. In this study, the means PTT at 1 and 2 kHz in group A and B were better than 20 dBHL, thus, DPOAEs amplitudes were present.

The results in group C and D (table 25, 26) showed no relationship between DPOAEs amplitudes and PTT in group C (except 1 kHz) and group D, because PTT in these groups fell in the range of 25-50 dBHL, thus, the presence of DPOAEs amplitudes were generally reduced or absent. These findings suggested that in ears with hearing impaired, good correlation between DPOAEs spectrum amplitudes and PTT when the hearing threshold were less than 20 dBHL or greater than 50 dBHL. However, the agreement between the DPOAEs amplitudes and PTT was found to be poorer for hearing loss in the range of 25 to 50 dBHL. Moreover, different pathology and etiology of the hearing loss also appeared to be a significant factor in determining the change in DPOAEs (16).

CHAPTER VI

CONCLUSION

The purpose of this study was to investigate the relationships between CEOAEs and DPOAEs with a comparison to pure tone thresholds in the same group of normal hearing and hearing impaired adults. The findings of this study were discussed according to data reported in the literature. The results from this study suggested the following conclusions:

1. The CEOAEs and DPOAEs amplitudes at 1-4 kHz in ears with hearing impaired were lower than those in normal hearing group, although the PTTs were less than 25 dBHL.

2. The CEOAEs and DPOAEs amplitudes were correlated in the same ear.

3. The DPOAEs were more robust than the CEOAEs in the high frequency

4. The CEOAEs should be more sensitive in detecting early stages of hearing loss

5. When the hearing threshold was less than 20 dBHL, the presence of CEOAEs spectrum amplitudes suggested good prediction, and when hearing threshold fell in the range of 25-35 dBHL CEOAEs spectrum amplitudes varied which suggested poor prediction. At hearing threshold greater than 35 dBHL, CEOAEs spectrum amplitudes were absent.

6. When the hearing threshold was less than 20 dBHL, the presence of DPOAEs amplitudes suggested good prediction, and when hearing threshold fell in the

range of 25-50 dBHL DPOAEs amplitudes varied which suggested poor prediction. At hearing threshold greater than 50 dBHL, DPOAEs amplitudes were absent.

7. Different pathology and etiology of the hearing loss may appear to be a significant factor in determining the change in CEOAEs and DPOAEs amplitudes.

Recommendation

The following recommendation for future study are suggested:

1. The routine audiological evaluation in hearing impaired subjects should include OAEs in the standard test to detect peripheral auditory function.

2. To generalize the relationship between pure tone thresholds and CEOAEs or DPOAEs characteristics, other pathological and etiological factors of hearing impairment should be examined.

3. Future study should be focused on benefit of CEOAEs and DPOAEs for screening purpose and monitoring change in the cochlea.

4. More number of subjects in the group of flat audiogram are suggested.

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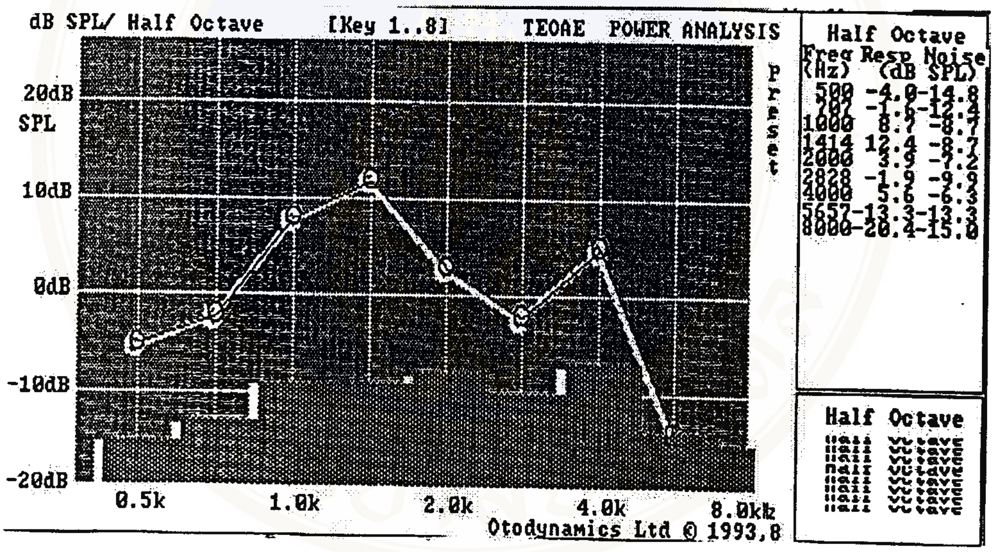
APPENDIX A

1. CEOAEs response level: A measure in dBSPL of the averaged RMS (root mean squared) amplitudes of the 260 waveforms relative to the calibration values of the probe

2. CEOAEs spectrum amplitudes: The level of signal and noise at the same half octave frequency eg., at 1 kHz CEOAEs spectrum amplitudes = 17.4 dBSPL (Figure 10)



```
   Half Octave
Freq Resp Noise
(Hz)   (dB SPL)
 500 -4.0-14.8
 707 -1.6-12.4
1000  8.7 -8.7
1414 12.4 -8.7
2000  3.9 -7.2
2828 -1.9 -9.9
4000  5.6 -6.3
5657-13.3-13.3
8000-20.4-15.0
```

Figure A-1 An example of the half octave analysis, the OAEs signal are plotted in line curve and the mean RMS are plotted in histogram

3. Half octave analysis: A histogram of the mean noise level and a graph of mean signal level at the same half octave

4. DP gram: A graph of the amplitude of DPOAEs and noise level plotted against frequencies of f2, instead of the geometric mean of f1 and f2, reflecting the frequencies range of the conventional audiogram. An example was shown in Figure 8

5. DPOAEs amplitudes: Calculated by subtracting corresponding noise from signal at each frequency

6. Sweep frequency: The frequency 'sweeps' steadily from one end of the range to the other at the rate of 1 octave per minutes.

7. Cochlear SNHL: The impairment of the preneural mechanical elements of the cochlea, which then causes a diminished auditory threshold for the perception of sound.

APPENDIX B

Table A-1 Raw data of pure tone thresholds at frequency 0.25 to 8 kHz in normal hearing adult subjects

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.50	1	2	4	6	8		.25	.50	1	2	4	6	8
S1	20	15	15	5	10	10	10	S31	20	15	10	5	5	0	0
S2	10	5	10	5	10	5	5	S32	10	10	5	15	10	15	25
S3	20	10	5	10	20	20	20	S33	15	5	0	15	15	15	15
S4	10	10	5	10	5	5	0	S34	5	5	0	10	10	15	15
S5	25	15	15	15	15	10	10	S35	15	10	0	5	5	15	15
S6	15	10	10	10	10	10	10	S36	10	5	5	5	10	5	5
S7	15	0	15	15	20	20	20	S37	10	10	10	10	10	5	5
S8	15	10	10	15	15	10	10	S38	5	10	10	5	0	0	0
S9	15	15	10	20	0	15	15	S39	15	15	20	15	10	15	15
S10	10	10	15	10	10	5	5	S40	5	10	10	10	0	5	5
S11	10	15	15	15	20	15	15	S41	15	5	10	15	0	0	0
S12	5	15	10	10	0	5	0	S42	5	5	15	15	15	0	0
S13	10	10	10	5	0	5	0	S43	5	5	15	15	15	10	10
S14	15	0	15	15	20	20	20	S44	10	10	15	15	15	20	20
S15	15	10	5	5	10	15	15	S45	10	10	5	0	0	0	0
S16	10	15	15	15	20	15	15	S46	15	10	5	5	0	0	0
S17	15	10	10	10	5	10	10	S47	10	5	5	15	15	10	10
S18	5	5	5	0	0	5	5	S48	10	10	15	10	15	10	10
S19	5	5	0	5	0	5	5	S49	10	5	0	5	5	5	5
S20	15	10	0	0	10	10	10	S50	10	10	10	10	5	15	15
S21	10	5	0	5	10	15	15	S51	5	10	10	5	5	10	10
S22	20	20	10	5	5	5	10	S52	10	10	10	5	5	0	0
S23	20	15	5	10	0	10	10	S53	5	5	10	5	0	0	0
S24	15	15	10	15	10	20	20	S54	15	10	10	5	10	5	5
S25	20	20	10	10	5	15	15	S55	20	10	10	5	5	10	10

Table A-1 Raw data of pure tone thresholds at frequency 0.25 to 8 kHz in normal hearing adult subjects (cont.)

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.50	1	2	4	6	8		.25	.50	1	2	4	6	8
S26	5	0	5	5	5	10	10	S56	5	10	10	5	0	10	0
S27	5	5	0	5	0	0	0	S57	15	10	5	5	5	5	5
S28	15	15	15	10	10	5	5	S58	15	15	5	10	5	0	0
S29	15	15	10	5	5	0	0	S59	15	15	15	15	5	5	5
S30	20	10	10	10	5	10	10	S60	20	25	20	20	20	20	25

Table A-2 Raw data of pure tone thresholds at frequency 0.25 to 8 kHz in subjects with 4-6 kHz audiometric notch

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.50	1	2	4	6	8		.25	.50	1	2	4	6	8
S1	25	20	15	20	20	35	25	S15	5	10	10	15	40	30	15
S2	10	25	20	20	45	60	35	S16	5	10	10	15	45	30	25
S3	20	15	20	30	65	40	15	S17	5	15	15	15	25	40	30
S4	15	25	25	30	40	50	15	S18	15	20	15	15	30	40	25
S5	10	20	20	20	30	35	15	S19	20	25	20	20	30	40	30
S6	20	15	20	30	65	70	15	S20	20	25	20	20	30	40	25
S7	20	25	25	35	55	40	20	S21	10	20	15	20	40	25	25
S8	15	20	25	30	50	40	20	S22	15	10	5	10	40	30	15
S9	15	15	15	10	45	20	20	S23	15	5	5	10	30	50	35
S10	15	20	15	15	35	15	15	S24	10	5	5	10	30	55	25
S11	15	20	15	15	35	15	15	S25	10	5	5	20	50	35	30
S12	25	10	15	15	35	20	20	S26	15	5	0	10	50	40	20
S13	20	20	15	15	45	30	20	S27	10	10	10	25	30	45	20
S14	5	20	20	25	50	25	20								

Table A-3 Raw data of pure tone thresholds at frequency 0.25 to 8 kHz in subjects with high frequency sloping

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.50	1	2	4	6	8		.25	.50	1	2	4	6	8
S1	25	20	25	20	20	40	85	S8	15	25	20	20	35	40	55
S2	15	25	5	25	45	50	70	S9	25	15	15	15	25	40	80
S3	20	15	10	10	55	65	70	S10	20	10	5	10	30	40	70
S4	20	15	15	10	20	40	50	S11	20	15	10	15	25	35	40
S5	15	15	10	10	10	55	70	S12	20	15	15	20	40	50	55
S6	25	25	10	15	25	50	60	S13	25	20	10	20	30	45	45
S7	5	10	10	10	15	35	40	S14	25	10	15	20	50	60	85

Table A-4 Raw data of pure tone thresholds at frequency 0.25 to 8 kHz in subjects with low frequency sloping

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.5	1	2	4	6	8		.25	.5	1	2	4	6	8
S1	35	35	25	20	20	25	25	S4	40	35	30	25	25	15	15
S2	35	30	25	25	20	20	25	S5	35	30	30	25	20	20	15
S3	40	40	30	25	15	10	10	S6	35	30	25	20	20	25	15

Table A-5 Raw data of pure tone thresholds at frequency 0.25-8 kHz in subjects with flat audiogram

No.	Frequency (kHz)							No.	Frequency (kHz)						
	.25	.5	1	2	4	6	8		.25	.5	1	2	4	6	8
S1	40	50	50	45	35	45	30	S8	33	35	35	35	30	30	30
S2	40	50	55	50	35	50	40	S9	30	35	30	35	35	25	30
S3	30	30	35	35	40	45	50	S10	35	30	35	35	30	30	30
S4	35	35	30	30	35	30	35	S11	35	30	30	35	35	25	30
S5	30	25	35	30	35	25	35	S12	30	25	30	35	40	25	30
S6	30	30	25	30	30	30	35	S13	35	30	25	30	30	30	35
S7	30	30	25	25	30	30	35								

Table A- 6 Raw data of CEOAEs response level (resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in normal hearing

No.	Resp	Frequency (kHz)						No.	Resp	Frequency (kHz)					
		1		2		4				1		2		4	
		PT	CE	PT	CE	PT	CE			PT	CE	PT	CE	PT	CE
S1	7.2	15	20.5	5	18.3	10	14.6	S11	12.2	15	17.8	15	17.2	20	16.5
S2	13.9	10	15.1	5	14.7	10	11.5	S12	11.6	10	12.8	10	12.0	0	13.7
S3	11.5	5	13.1	10	7.7	20	10.4	S13	10.8	10	12.8	5	11.1	0	9.6
S4	10.5	5	16.2	10	12.5	5	10.5	S14	11.4	15	13.0	15	12.6	20	10.5
S5	10.3	15	18	15	8.8	15	9.7	S15	8.5	5	9.8	5	9.6	10	8.3
S6	11.9	10	19.2	10	5.0	10	9.7	S16	13.0	15	7.2	15	4.9	20	7.2
S7	16.2	15	15.5	15	13.5	20	4.0	S17	14.0	10	17.1	10	9.1	5	7.5
S8	15.9	10	17.1	15	20.4	15	18.6	S18	18.4	5	18.9	0	13.2	0	6.4
S9	15.4	10	9.7	20	24.4	0	11.1	S19	8.8	0	17.3	5	19.6	0	5.3
S10	14.1	15	7.1	10	8.1	10	19.0	S20	11.2	0	8.4	0	5.5	10	8.5

Table A- 6 Raw data of CEOAEs response level (resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in normal hearing (cont.)

No.	Resp	Frequency (kHz)						No.	Resp	Frequency (kHz)					
		1		2		4				1		2		4	
		PT	CE	PT	CE	PT	CE			PT	CE	PT	CE	PT	CE
S21	11.2	15	13.9	5	14.2	10	5.6	S41	8.8	10	14.0	15	10.6	0	12.6
S22	15.6	10	12.2	5	12.0	5	10.8	S42	10.0	15	12.3	15	13.6	15	7.5
S23	15.1	5	17.4	10	11.1	0	11.9	S43	9.8	15	11.4	15	8.8	15	12.6
S24	8.7	5	8.5	15	6.6	10	12.6	S44	8.4	15	21.5	15	19.6	15	14.8
S25	8.5	15	10.6	10	10.9	5	7.6	S45	7.7	5	17.0	0	17.1	0	10.9
S26	14.2	10	12.1	5	10.9	5	9.6	S46	11.4	5	14.6	5	12.2	0	14.8
S27	14.8	15	16.2	5	12.5	0	13.9	S47	7.6	5	23.9	15	14.1	15	8.1
S28	8.2	10	12.5	10	7.7	10	7.7	S48	13.7	15	16.0	10	11.3	15	7.4
S29	9.5	10	16.6	5	9.9	5	7.3	S49	12.9	0	14.0	5	12.0	5	8.5
S30	10.8	15	11.8	10	12.9	5	7.8	S50	11.9	10	5.3	10	9.9	5	13.8
S31	8.8	10	11.3	5	13.1	5	7.4	S51	8.4	10	9.3	5	7.0	5	10.1
S32	10.0	5	17.9	15	18.3	10	7.6	S52	11.0	10	9.2	5	13.4	5	8.6
S33	9.8	0	13.7	15	12.4	15	9.6	S53	12.1	10	15.0	5	14.7	0	7.6
S34	8.4	0	14.9	10	16.0	10	12.3	S54	11.7	10	5.6	5	10.4	10	12.6
S35	7.7	0	11.6	5	14.6	5	9.9	S55	7.4	10	12.4	5	15.2	5	16.9
S36	11.4	5	12.8	5	9.6	10	13.0	S56	10.6	10	6.7	5	12.0	0	11.5
S37	7.6	10	11.7	10	8.3	10	9.5	S57	12.7	5	12.4	5	11.8	5	12.2
S38	13.7	10	9.4	5	16.3	0	17.4	S58	14.5	5	18.6	10	12.1	5	16.0
S39	12.9	20	9.9	15	12.4	10	16.1	S59	15.7	15	19.7	15	14.7	5	12.5
S40	11.9	10	15.4	10	11.6	0	15.5	S60	12.6	20	12.3	20	12.7	20	10.6

Table A-7 Raw data of CEOAEs response level (Resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in 4-6 kHz audiometric notch

No.	Resp	Frequency (kHz)					
		1		2		4	
		PT	CE	PT	CE	PT	CE
S1	4.7	15	15.0	20	15.2	20	4.4
S2	13.9	20	8.4	20	12.7	45	
S3	8.4	20	9.4	30	10.8	65	
S4	9.2	25	8.0	30	11.2	40	
S5	6.5	20	16.4	20	12.4	30	
S6	15.2	20	11.5	30	11.5	65	
S7	15.1	25	11.4	35	12.0	55	
S8	16.9	25	6.6	30	11.6	50	
S9	7.9	15	16.0	10	13.9	45	
S10	15.3	15	15.2	15	14.6	35	
S11	10.1	15	11.7	15	14.0	35	
S12	9.6	15	11.6	15	15.1	35	
S13	10.3	15	14.5	15	13.7	45	
S14	4.9	20	10.9	25	13.9	50	4.1
S15	3.8	10	18.7	15	12.9	40	
S16	5.6	10	15.2	15	11.6	45	
S17	5.1	15	12.7	15	12.2	25	
S18	3.3	15	14.6	15	13.1	30	
S19	3.7	20	7.9	20	12.5	30	
S20	6.9	20	5.8	20	11.5	30	4.8
S21	8.5	15	11.5	20	12.3	40	
S22	4.7	5	16.0	10	11.7	40	
S23	4.9	5	19.7	10	12.5	30	6.9
S24	12.9	5	21.1	10	12.7	30	
S25	8.5	5	23.4	20	7.6	50	
S26	6.9	0	18.9	10	13.5	50	
S27	8.5	10	16.8	25	7.3	30	5.7

Table A-8 Raw data of CEOAEs response level (Resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in high frequency sloping

No.	Resp	Frequency (kHz)						No.	Resp	Frequency (kHz)					
		1		2		4				1		2		4	
		PT	CE	PT	CE	PT	CE			PT	CE	PT	CE	PT	CE
S1	6.4	25	14.2	20	15.5	20		S8	10.8	20	22.1	20	13.9	35	
S2	4.0	5	12.7	25	13.4	45		S9	10.5	15	18.9	15	12.8	25	
S3	4.5	10	23.1	10	17.7	55	5.6	S10	3.5	5	21.6	10	16.4	30	
S4	7.2	15	17.7	10	16.6	20		S11	12.7	10	16.7	15	15.3	25	
S5	3.2	10	20.5	10	15.4	10		S12	4.9	15	17.1	20	18.7	40	
S6	4.4	10	22.3	15	14.3	25	3.3	S13	12.9	10	16.9	20	7.8	30	
S7	9.1	10	20.7	10	16.7	15		S14	4.9	15	11.6	20	7.6	50	

Table A-9 Raw data of CEOAEs response level (Resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in low frequency sloping

No.	Resp	Frequency (kHz)						No.	Resp	Frequency (kHz)					
		1		2		4				1		2		4	
		PT	CE	PT	CE	PT	CE			PT	CE	PT	CE	PT	CE
S1	3.4	25	6.6	20	12.2	20	14.4	S4	9.2	30	3.0	25		25	17.5
S2	4.4	25	6.0	25	9.2	20	5.3	S5	4.0	30	6.2	25	9.2	20	5.3
S3	10.2	30	7.9	25	8.9	15	17.1	S6	3.2	25	4.2	20	12.2	20	14.4

Table A-10 Raw data of CEOAEs response level (Resp), pure tone threshold (PT) and CEOAEs (CE) spectrum amplitudes at frequency 1-4 kHz in flat audiometry

No.	Resp	Frequency (kHz)						No.	Resp	Frequency (kHz)					
		1		2		4				1		2		4	
		PT	CE	PT	CE	PT	CE			PT	CE	PT	CE	PT	CE
S1	3.8	50		45	6.1	35		S8	4.4	35	4.7	35		30	11.2
S2	3.1	55		50		35	3.1	S9	4.5	30	8.7	35	5.4	35	8.4
S3	3.4	35	4.0	35		40		S10	6.7	35		35	7.8	30	10.5
S4	4.2	30	3.1	30		35	4.5	S11	6.7	30		35	3.1	35	8.3
S5	5.2	35	7.4	30	4.1	35	6.1	S12	4.7	30	4.9	35		40	7.6
S6	6.4	25	3.4	30	3.4	30		S13	6.4	25	3.4	30	3.4	30	
S7	6.2	25		25	10.1	30	6.5								

Table A-11 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in normal hearing

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S1	15	11.8	5	20.2	10	16.9	10	20.3	S10	15	12.9	10	17.3	10	22.1	5	26.7
S2	10	22.6	5	24.8	10	14.7	5	24.2	S11	15	10.8	15	25.9	20	19.1	15	26.2
S3	5	23.0	10	18.7	20	12.5	20	19.6	S12	10	20.0	10	22.3	0	16.5	5	26.3
S4	5	17.4	10	16.3	5	14.7	5	25.2	S13	10	14.7	5	25.6	0	19.3	5	25.6
S5	15	19.5	15	22.0	15	24.4	10	17.4	S14	15	7.9	15	17.1	20	12.5	20	17.9
S6	10	21.8	10	19.7	10	13.6	10	23.5	S15	5	18.9	5	16.5	10	14.4	15	27.2
S7	15	13.9	15	25.9	20	13.3	20	16.9	S16	15	13.1	15	17.2	20	12.6	15	19.0
S8	10	18.6	15	27.2	15	24.7	10	24.9	S17	10	20.2	10	16.3	5	12.1	10	19.5
S9	10	11.0	20	25.6	0	19.5	15	27.6	S18	5	24.1	0	25.6	0	15.8	5	18.1

Table A-11 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in normal hearing (cont)

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S19	0	21.4	5	25.0	0	21.4	5	14.1	S40	10	12.4	10	18.9	0	19.4	5	28.6
S20	0	15.7	0	22.1	10	19.3	10	22.4	S41	10	14.4	15	16.3	0	20.1	0	22.0
S21	0	14.8	5	21.4	10	13.3	15	20.6	S42	15	11.4	15	16.0	15	18.4	0	23.6
S22	10	18.0	5	24.2	5	24.5	5	25.9	S43	15	25.5	15	18.9	15	21.8	10	21.3
S23	5	19.7	10	23.5	0	21.3	10	27.5	S44	15	21.2	15	16.3	15	20.2	20	13.0
S24	10	13.8	15	20.1	10	26.5	20	20.9	S45	5	19.4	0	19.8	0	23.9	0	27.9
S25	10	14.0	10	25.8	5	24.2	15	24.8	S46	5	14.7	5	22.4	0	24.6	0	25.4
S26	5	19.7	5	25.9	5	21.1	10	26.4	S47	5	21.2	15	16.9	15	13.5	10	15.3
S27	0	19.1	5	19.7	0	14.1	0	30.9	S48	15	20.6	10	14.8	15	18.5	10	19.1
S28	15	17.9	10	16.6	10	20.3	5	23.6	S49	0	15.0	5	14.5	5	16.4	5	19.7
S29	10	20.7	5	23.2	5	13.9	0	18.7	S50	10	19.3	10	17.2	5	14.0	15	22.3
S30	10	17.4	10	19.1	5	13.6	10	23.2	S51	10	20.0	5	19.7	5	15.8	10	27.5
S31	10	15.6	5	15.9	5	17.5	0	20.4	S52	10	11.1	5	21.6	5	20.2	0	20.7
S32	5	19.4	15	21.9	10	14.6	15	18.4	S53	10	12.4	5	21.2	0	23.2	0	26.2
S33	0	20.4	15	22.4	15	15.4	15	20.5	S54	10	11.0	5	15.5	10	25.0	5	29.2
S34	0	19.0	10	20.1	10	11.2	15	22.5	S55	10	24.0	5	17.2	5	14.1	10	20.8
S35	0	16.2	5	15.8	5	14.8	15	22.4	S56	10	13.9	5	25.9	0	24.1	10	27.0
S36	5	15.4	5	15.2	10	15.1	5	27.0	S57	5	17.3	5	26.9	5	25.3	5	27.1
S37	10	10.5	10	10.8	10	12.1	5	16.0	S58	5	18.0	10	22.7	5	23.6	0	28.1
S38	10	12.9	5	17.3	0	22.1	0	26.7	S59	15	15.2	15	25.7	5	25.9	5	27.2
S39	20	10.8	15	15.9	10	19.1	15	28.2	S60	20	20.2	20	20.6	20	20.0	20	22.0

Table A-12 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in 4-6 kHz audiometric notch

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S1	15	12.9	20	17.1	20	16.8	35	19.6	S15	10	16.4	15	19.3	40	16.0	30	14.9
S2	20	15.0	20	17.1	45		60		S16	10	26.1	15	20.6	45	10.6	30	17.9
S3	20	13.8	30	16.5	65		40		S17	15	20.1	15	19.2	25	13.2	40	
S4	25	13.6	30	16.0	40		50		S18	15	15.2	15	15.4	30	13.5	40	6.1
S5	20	14.9	20	17.4	30	11.0	35	5.8	S19	20	13.2	20	15.5	30	12.0	40	6.1
S6	20	13.7	30	13.4	65		70		S20	20	14.0	20	15.3	30	12.0	40	10.9
S7	25	12.3	35	16.1	55		40		S21	15	17.0	20	14.4	40		25	19.9
S8	25	11.0	30	16.2	50	12.3	40	17.9	S22	5	18.7	10	22.1	40	5.6	30	19.5
S9	15	11.0	10	24.1	45	8.6	20	14.4	S23	5	18.7	10	24.9	30	15.5	50	19.8
S10	15	10.2	15	19.4	35	8.6	15	15.6	S24	5	19.0	10	23.9	30	15.3	55	
S11	15	11.5	15	19.4	35	8.8	15	19.0	S25	5	13.7	20	21.2	50		35	
S12	15	10.8	15	15.8	35	3.9	20	20.7	S26	0	16.9	10	20.0	50		40	
S13	15	16.4	15	17.4	45	10.6	30	14.9	S27	10	18.5	25	15.4	30	14.5	45	17.0
S14	20	25.0	25	14.9	50		25	16.0									

Table A-13 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in high frequency sloping

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S1	20	16.7	20	18.4	20	14.4	40	17.9	S8	20	23.8	20	17.4	35	7.8	40	26.0
S2	25	20.8	25	16.7	45	9.4	50	23.8	S9	15	20.5	15	16.8	25	8.9	40	18.0
S3	10	25.5	10	20.1	55	6.6	65		S10	5	25.7	10	18.9	30	11.9	40	18.6
S4	10	20.7	10	20.6	20	16.5	40	21.5	S11	10	22.6	15	17.5	25	10.6	35	18.9
S5	10	24.4	10	18.2	10	14.2	55		S12	15	21.5	20	16.9	40	12.5	50	
S6	15	25.5	15	17.5	25	12.4	50		S13	10	23.2	20	18.1	30	11.8	45	12.1
S7	10	24.0	10	20.4	15	13.5	35	18.8	S14	15	22.8	20	16.7	50	12.2	60	

Table A-14 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in low frequency sloping

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S1	25	5.2	20	11.6	20	20.4	25	15.7	S4	30	4.1	25		25	20.3	15	32.1
S2	25	6.4	25	24.0	20	7.4	20	14.1	S5	30	5.6	25	22.0	20	7.5	20	14.7
S3	30	7.2	25		15	19.1	10	27.8	S6	25	5.2	20	11.8	20	20.2	25	15.1

Table A-15 Raw data of pure tone threshold (PT) and DPOAEs (DP) amplitudes at frequency 1-6 kHz in flat audiogram

No	Frequency (kHz)								No	Frequency (kHz)							
	1		2		4		6			1		2		4		6	
	PT	DP	PT	DP	PT	DP	PT	DP		PT	DP	PT	DP	PT	DP	PT	DP
S1	50		45		35	7.4	45	17.6	S8	35	4.7	35	13.5	30	16.0	30	27.9
S2	55		50		35	16.5	50		S9	30	8.7	35	16.6	35	28.9	25	28.1
S3	35	4.0	35		40		45		S10	35		35	13.9	30	16.6	30	32.2
S4	30	3.1	30		35	17.7	30	16.8	S11	30		35	9.8	35	16.2	25	20.0
S5	35	7.4	30	13.2	35	22.0	25		S12	30	4.9	35	8.1	40	18.0	25	16.3
S6	25	3.4	30	15.0	30	23.8	30	27.0	S13	25	3.4	30	15.0	30	23.8	30	27.0
S7	25		25	13.9	30	23.9	30	30.3									

BIOGRAPHY

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