COMPARISONS OF DISTORTION PRODUCT OTOACOUSTIC EMISSIONS (DPOAE) RESULTS EVOKED BY PURE TONES (PT) AND FREQUENCY MODULATED (FM) TONES IN NORMAL HEARING ADULTS

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by

DARSHAINI A/P PANNIRSELVAN

Thesis submitted in fulfilment of the requirements

for the degree of Bachelor of Health Science in Audiology (Honours)

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CERTIFICATION

This is to certify that dissertation entitled 'Comparisons of DPOAE Results Evoked by Pure Tones (PT) and Frequency Modulated (FM) Tones in Normal Hearing Adults' is the project done by DARSHAINI A/P PANNIRSELVAN from September 2024 to July 2025 under my supervision. We have read this dissertation and that in our opinion, it fulfils the acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation to be submitted in partial fulfilment for the degree of Bachelor of Health Sciences (Honours) (Audiology). Research work and collection of data belong to the Universiti Sains Malaysia.

. ...

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Date: 02/10/2025	Date: 02/10/2025

DECLARATION

I hereby declare that the work has been done by myself, all the results are of my own investigation and any ideas or quotation from others' work are fully acknowledged according to the standard referring practices of the discipline. I also declare that it has not been submitted as a whole in previous or concurrently for any other degrees in any institutions. I acknowledge that that the research work and collection of data belong to Universiti Sains Malaysia (USM).

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ABSTRACT

The distortion product otoacoustic emission (DPOAE) is a valuable audiological test for assessing the function of outer hair cells and other clinical applications. Stimuli such as pure tones are typically used to record DPOAE. Frequency modulated (FM) tones have recently been introduced as alternative stimuli and are now incorporated into certain commercially available DPOAE devices. However, the extent to which the FM tones surpass the conventional pure tones in effectiveness for DPOAE recordings remains insufficiently established. Therefore, this study aimed to compare the DPOAE results elicited by pure tones and FM tones. The test duration was also compared between the two stimuli. In this study that employed a repeated measures design, 32 healthy young adults (64 ears) were enrolled. All of them demonstrated normal hearing sensitivity and normal middle ear function. The DPOAE testing was carried out using the Sentiero Advanced device (Path Medical, Germany). During the testing, both pure tones and FM tones were presented at 55 dB HL with equal primary tone levels. The DPOAE responses were recorded at frequencies of 1 kHz to 10 kHz under three different noise condition such quiet, 40 dB SPL and 60 dB SPL. The test duration for each stimulus was also recorded. In the quiet condition, PT stimuli produced significantly higher SNR values than FM stimuli at 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz, 8 kHz and 10 kHz ($p < 0.05$). Under 40 dB SPL, PT showed significantly higher SNR at 1 kHz, 3 kHz, 4 kHz, 5 kHz, 7 kHz and 8 kHz, whereas FM was significantly higher at 2 kHz ($p = 0.014$) and 9 kHz ($p = 0.019$). At 60 dB SPL, PT stimuli produced significantly greater SNR values at 4 kHz ($p = 0.001$) and 6 kHz ($p = 0.047$). For amplitude, PT stimuli elicited significantly higher responses at 4 kHz and 5 kHz in both quiet and 40 dB SPL conditions ($p < 0.05$), while FM was significantly higher only at 8 kHz in the 60 dB SPL condition (p

= 0.021). FM stimuli required significantly longer test durations in all conditions where quiet (median = 48.5 s), 40 dB SPL (76.25 s) and 60 dB SPL (183.75 s) compared to PT (38 s, 39 s and 94.25 s respectively, $p < 0.001$). In conclusion, it appears that the conventional pure tones are still the preferred stimuli for recording DPOAE as it produces emissions with significantly higher amplitudes and higher SNRs in short durations.

ABSTRAK

Distortion Product Otoacoustic Emission (DPOAE) merupakan satu ujian audiologi yang penting untuk menilai fungsi sel rerambut luar pada koklea serta mempunyai pelbagai aplikasi klinikal. Secara lazimnya, rangsangan nada tulen digunakan untuk merekodkan DPOAE. Namun begitu, nada modulasi frekuensi (FM) telah diperkenalkan sebagai rangsangan alternatif dan telah digunakan dalam beberapa peranti DPOAE yang tersedia secara komersial. Walau bagaimanapun, tahap keberkesanan nada FM berbanding nada tulen konvensional dalam pemerolehan DPOAE masih belum dapat dipastikan sepenuhnya. Oleh itu, kajian ini dijalankan untuk membandingkan keputusan DPOAE yang diperoleh melalui pengunaan nada tulen dan nada FM. Tempoh ujian bagi setiap jenis rangsangan turut dibandingkan. Kajian ini menggunakan reka bentuk ukuran berulang dan melibatkan 32 orang dewasa yang sihat (64 telinga). Semua peserta mempunyai pendengaran yang normal serta fungsi telinga tengah yang normal. Ujian DPOAE telah dijalankan menggunakan peranti Sentiero Advanced (Path Medical, Germany). Sepanjang ujian, rangsangan awal bagi kedua - dua nada tulen dan nada FM ditetapkan pada 55 dB SPL dengan aras nada primer yang sama. Tindak balas DPOAE direkodkan pada frekuensi antara 1 kHz hingga 10 kHz dalam tiga keadaan bunyi yang berbeza iaitu keadaan senyap, 40 dB SPL dan 60 dB SPL. Tempoh ujian bagi setiap jenis rangsangan turut direkodkan. Dalam keadaan senyap, rangsangan PT menghasilkan SNR yang jauh lebih tinggi berbanding rangsangan FM pada frekuensi 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz, 8 kHz dan 10 kHz ($p < 0.05$). Dalam keadaan 40 dB SPL, PT menunjukkan SNR yang lebih tinggi pada 1 kHz, 3 kHz, 4 kHz, 5 kHz, 7 kHz dan 8 kHz, manakala FM lebih tinggi secara signifikan pada 2 kHz ($p = 0.014$) dan 9 kHz ($p = 0.019$). Dalam keadaan 60 dB SPL, PT menghasilkan nilai SNR yang lebih tinggi secara signifikan pada 4 kHz

($p = 0.001$) dan 6 kHz ($p = 0.047$). Dari segi amplitud, PT menghasilkan tindak balas yang lebih tinggi secara signifikan pada 4 kHz dan 5 kHz dalam keadaan senyap dan 40 dB SPL ($p < 0.05$), manakala FM hanya menunjukkan amplitud yang lebih tinggi secara signifikan pada 8 kHz dalam keadaan 60 dB SPL ($p = 0.021$). Rangsangan FM juga memerlukan tempoh ujian yang lebih lama secara signifikan dalam semua keadaan, iaitu keadaan senyap (median = 48.5 s), 40 dB SPL (76.25 s), dan 60 dB SPL (183.75 saat), berbanding dengan PT masing-masing sebanyak 38 s, 39 s dan 94.25 s ($p < 0.001$). Kesimpulannya, nada tulen konvensional masih menjadi pilihan utama untuk ujian DPOAE kerana mampu menghasilkan respon yang lebih tinggi dari segi amplitud dan SNR serta tempoh masa yang lebih singkat.

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LIST OF SYMBOLS AND ABBREVIATIONS

~	Approximately
=	Equal
>	Greater Than
>	Greater Than or Equal To
<	Lesser Than
≤	Lesser Than or Equal To
s	Second
%	Percentage
±	Plus-or-Minus
dB	Decibel
dB HL	Decibel Hearing Level
dB SPL	Decibel Sound Pressure Level
DPOAE	Distortion Product Otoacoustic Emission
FM	Frequency Modulated
FMDPOAE	Frequency Modulated Distortion Product Otoacoustic Emission
kHz	Kilohertz
mDPOAE	Multi-Tone Pair Distortion Product Otoacoustic Emission
NICU	Neonatal Intensive Care Unit
OAE	Otoacoustic Emission
PTA	Pure Tone Audiometry
PT	Pure Tone
SCN	Special Care Nurseries
SD	Standard Deviation

SE	Standard Error
SNR	Signal to Noise Ratio
USM	Universiti Sains Malaysia

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

All five senses play an important role in living a fulfilling lifestyle. Hearing is one of the crucial senses for overall development especially for individual as hearing loss can reduce the impact on their development and giving them the best chance to thrive socially, emotionally and academically. Among various types of OAE, distortion product otoacoustic emission (DPOAE) are widely utilized due to its effectiveness in assessing cochlear function and detecting hearing impairments even in noisy settings. According to Abdala (2001), DPOAE testing is an effective tool for detecting potential hearing loss in individuals.

Although, DPOAE does not directly measure hearing, it correlates with the auditory function and serves as a valuable diagnostic tool in audiology clinics. DPOAE is an objective approach that assesses the hearing functionality by delivery a straightforward "pass" or "refer" outcome which is generated without relying on subjective analysis. DPOAE offer basic hearing screening data and more detailed diagnostic insights, particularly when there is a concern of hearing loss. This simplicity makes it suitable for patients unable to provide reliable behavioural responses such as newborn, non-cooperative children or individuals with developmental disabilities. Additionally, DPOAE help audiologists to differentiate between sensory and neural cases of sensorineural hearing loss as well as nonorganic hearing loss.

Nowdays, there are options to record DPOAE using the conversational pure tones or frequencies modulated tones. However, it remains unclear which stimulus types offer better in recording OAE. The accuracy of DPOAE testing can be affected by background noise such as conversations, machinery or other ambient noises. Background noise can lower the signal-to-noise ratio (SNR) and affect amplitude, which may lead to inaccurate result. This issue is particularly significant in busy clinical environments or paediatric settings such Neonatal Intensive Care Unit (NICU) and Special Care Nurseries (SCN), where constant noise from medical equipment can interfere with the testing. Identifying a stimulus that improves the signal to noise ratio and minimizes noise interference could improve testing reliability and ensure timely intervention for infants and other vulnerable patients.

1.2 Problem Statement

In the current audiology practice, DPOAE is widely used to assess cochlear health, in diagnosing hearing impairments in both clinical and screening settings. Conventional pure tones have been used as stimuli in DPOAE testing due to its simplicity and consistency in generating otoacoustic emissions. However, frequency modulated (FM) tones have the potential to improve DPOAE results (Janssen, 2015). The superiority of this test lies in achieving higher amplitudes, improved SNR and shorter test duration. However, research on this topic in the current literature is extremely limited. Despite this, the FM DPOAE testing is currently only available on the Sentiero Advanced device. A previous study by Baker (2021)has shown inconsistent results when comparing tests with and without FM tones. One possible reason for this could be the small sample size, (n=11). More research is needed to explore this area further. Additionally, it is still unclear how the FM DPOAE performs under different levels of background noises compared to conversional pure tone DPOAE.

In clinical settings with high patient volumes, minimizing test duration is important especially for young children or individuals with limited attention spans. Therefore, this study aims to evaluate the SNR, amplitude and test duration of different stimuli in DPOAE screening from 1 kHz to 10 kHz across various noise condition including in quiet, 40 dB SPL noise and 60 dB SPL noise conditions. The findings would enhance clinical outcomes, ensuring more reliable hearing screening across diverse settings, including challenging environments with persistent background noises.

1.3 Research Questions

This study aimed to address the following research questions:

1. Does the amplitude of DPOAE responses differ between pure tones and frequency modulated tones in both quiet and noisy conditions?
2. Does the signal to noise ratio (SNR) of DPOAE results differ between pure tones and frequency modulated tones across various sound levels?
3. Is there a difference in the test duration between pure tones and frequency modulated tone when conducting DPOAE measurements?

1.4 Study Objective

1.4.1 General Objective

This study aimed to compare the performance of DPOAE when elicited by pure tones and frequency modulated tones in quiet and noisy conditions.

1.4.2 Specific Objectives

1. To compare the amplitude of DPOAE between pure tones and frequency modulated tones in quiet and noisy conditions.
2. To compare the signal to noise ratio (SNR) of DPOAE between pure tones and frequency modulated tones in quiet and noisy conditions.
3. To compare the test duration of DPOAE between pure tones and frequency modulated tones in quiet and noisy conditions.

1.5 Hypothesis

1.5.1 Null Hypothesis

1. There is no significant difference in DPOAE amplitudes between pure tones and frequency modulated tones in quiet and noisy conditions.
2. There is no significant difference in DPOAE SNR between pure tones and frequency modulated tones in quiet and noisy conditions.
3. There is no significant difference in DPOAE test duration between pure tones and frequency modulated tones in quiet and noisy conditions.

1.5.2 Alternative Hypothesis

1. There is significant difference in DPOAE amplitudes between pure tones and frequency modulated tones in quiet and noisy conditions.
2. There is significant difference in DPOAE SNR between pure tones and frequency modulated tones in quiet and noisy conditions.
3. There is significant difference in DPOAE test duration between pure tones and frequency modulated tones in quiet and noisy conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Distortion Product Otoacoustic Emission (DPOAE)

This research focuses on DPOAE, which occur when two specific tones are presented simultaneously to the ear. These emissions arise due to nonlinear responses within the inner ear, particularly from the basilar membrane motion and outer hair cells which distort the original tones and generate a third frequency known as the distortion product. By presenting two primary tones, labelled f_1 and f_2 and analyzing the sound spectrum within the ear canal. In a linear cochlear system, only the original frequencies f_1 and f_2 would be measurable. However, in a healthy cochlea additional frequency known as intermodulation distortion frequencies are observed, with the most prominent $2f_1 - f_2$ and $f_2 - f_1$ (Rao, Tusler & Formo, 2014). Significantly, in a healthy cochlear, the primary distortion product $2f_1 - f_2$ may appear only 30 to 40 dB below the primary tones, highlighting a robust nonlinear response characteristic of normal auditory function (Roeser, Valente & Hosford-Dunn, 2007).

This emission, generally recorded about 50 dB lower than f_1. Optimal DPOAE responses occur when the f_2/f_1 frequency ratio is around 1.22 with L_1 and L_2 usually set up to 65 dB SPL and 50 dB SPL respectively. For accurate measurement, DPOAE commonly recorded over a frequency range of 1 kHz to 6 kHz by sweeping through the primary tone pairs multiple times, enhancing signal quality and minimizing the background noise. The primary tones are filtered out during recording to measure only the distortion product frequency, with a minimum DPOAE amplitude of 6 dB above the noise floor at each f_2 is considered an indicator of normal cochlear function. Furthermore, middle ear conditions must be considered, as conductive element can affect DPOAE results where refer DPOAE may suggest either poor outer hair cell function which leads to cochlear dysfunction or middle ear pathology (Kramer & Brown, 2019).

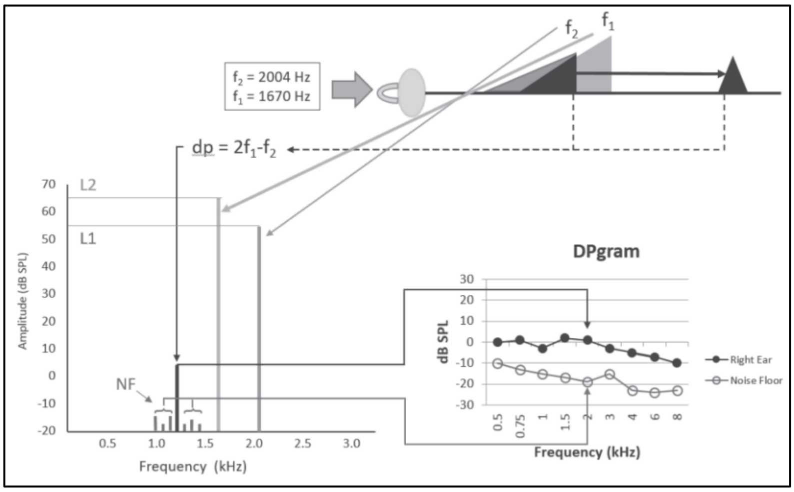


Figure 2.1: The upper panel shows DPOAE generation on the basilar membrane, where tones close in frequency (1670 and 2004) Hz produce a distortion product that travels back the ear canal and generates a traveling wave further along the basilar membrane at the ($2f_1-f_2$) distortion products in the er canal. The lower right panel provides a typical DPOAE recording from a normal hearing right ear, with a DP-gram showing DPOAE amplitude and noise levels as a function of the f_2 primary tone.

Adapted from: Kramer, S. & K. Brown, D. (2019) Audiology Science to Practice Third Edition. Third Edition.

2.2 Effect of Background Noise on DPOAE Accuracy

The measurement of DPOAE is highly sensitive to background noise in the testing environment (Dhar & Hall, 2018). Hearing screenings are commonly conducted in noisy or acoustically unsuitable environments due to controlled testing spaces are not always accessible. Consequently, the lack of proper testing conditions can affect the accuracy and reliability of the screening results. For example, background noise can interfere with the detection of DPOAE responses, resulting in higher “refer” rates and also longer test durations.

The issue is particularly critical in the neonatal intensive care unit (NICU), where noise levels can peak up to 120 dB. This is far above the American Academy of Paediatrics’ recommended maximum limit of 45 dB, which is similar to the sound of an ambulance siren. Moreover, average noise levels in NICU were reported by Mayhew et al. (2022) to be 83.5 dB during the day, 83 dB in the evening and 80.9 dB at night.

In this context, the signal-to-noise ratio (SNR) plays an important role for ensuring the reliability of DPOAE measurements. SNR defined as the ratio of the DPOAE signal’s strength to the background noise, determines the clarity and accuracy of the test results. A high SNR indicates that the otoacoustic emissions are more distinguishable from background noise, thereby leading to more accurate and consistent result. Typically, an SNR of at least 6 dB is considered acceptable for interpreting DPOAE measurements effectively.

2.3 Frequency Modulated Distortion Product Otoacoustic Emission (FM DPOAE)

The literature on frequency modulation in DPOAE is extremely limited. According to Janssen (2015), FM DPOAE overcomes the limitation of the interference from a secondary distortion product source at $2f_1 – f_2$ that can overlap with the primary signal in conventional DPOAE testing. The FM DPOAE overcomes this limitation by employing the frequency modulated primary tones instead of the fixed frequency tones. In this approach, FM DPOAE uses frequency-modulated primary tones (f1 and f2), which shift slightly within a up and down over time (±100 Hz) at a modulation rate (~1.5 Hz). This frequency modulation introduces a phase shift that effectively suppresses the contribution of the secondary distortion source. As a result, the DPOAE measure is predominantly generated from the targeted f_2 location in the cochlea, leading to more accurate and specific assessments of cochlear health.

In a more recent study, Baker (2021) compares multi-tone distortion product otoacoustic emission (mDPOAE) with and without frequency modulation (FM) in young children with normal hearing. The study found no significant differences in amplitude or test duration with FM. However, the SNR was slightly better without FM was higher than with FM suggesting a better response without modulation. The small sample size due to the interruptions from the COVID-19 pandemic, limited the statistical power of the study highlighting the need for further research to validate these findings and assess their clinical applications.

2.4 DPOAE Fine Structure

The DPOAE fine structure, known as an interference pattern, resulting from the phase interaction between distortion and reflection components. When these components are out of phase, they cancel each other and reduce the response (dips), while in-phase summation leads to enhanced responses (peaks). Therefore, the selected test frequencies influence the observed phase relationship and amplitude variation (Abdala, Mishra & Williams, 2009).

Marcrum et al. (2021) analysed that using frequency modulation approach demonstrates a clear advantage over the conventional method in its ability to reduce the depth of DPOAE fine structure without decreasing the overall amplitude of the signal. By dynamically modulating the f_2 primary tone frequency using a sine wave, the FM method disrupts the fixed interference patterns between distortion and reflection components. This disruption minimizes the interference patterns caused by overlapping cochlear mechanisms, reducing the impact of fine structure variability while maintain a consistent DPOAE amplitude. As a result, FM should provide more stable amplitude across various frequencies and levels enhancing clinical applicability. This stability is particularly significant because less variability in fine structure improves the accuracy of hearing assessments, addressing one of the challenges faced when using conventional methods.

Conversely, the conventional approach which uses fixed primary tones such f_1 and f_2 with static frequency (f_1 and f_2) and intensity levels (L_1 and L_2), generates higher peak amplitudes at some frequencies. However, this approach is highly sensitive to fine structure interactions, making it more prone to variability, particularly where destructive interference occurs. This sensitivity can lead to inconsistent result with significant dips and peaks influencing the reliability of measurements. Although conventional methods are easier to apply but highly sensitive at fine structure interactions. This sensitivity can result increased occurrences of false positives or false negatives, reducing effectiveness in accurately detecting cochlear problem.

CHAPTER 3

METHODOLOGY

3.1 Research Design

This study employed a repeated-measures research design, where the subjects of this study were measured several times to assess the performance of DPOAE when elicited by pure tones and frequency modulated tones under both quiet and noisy conditions.

3.2 Study Location

This study was conducted in the sound-treated room of the Audiology Clinic at the Pusat Pengajian Sains Kesihatan, Universiti Sains Malaysia.

3.3 Study Population

This study recruited normal hearing students from USM Kubang Kerian, Kelantan.

3.4 Subject Criteria

Table 3.1 Inclusion and exclusion criteria for study participants

Inclusion criteria	**Exclusion criteria**
Aged 20 - 24 years old	Failed PTA (>20 dB HL)
No history related to otological	Participant who refuses to cooperate during the test
Willing to participate voluntarily	3. Abnormal tympanogram

3.5 Sample Size Estimation

The sample size for this study was calculated by using the MedCalc software (version 23.0.8) and based on the study by Rhoades et al. (1998). The calculation was conducted with a confidence level of 95 % (α= 0.05), power of 90 % (β=0.9), the mean difference of 4.4 dB SPL and standard deviation of difference of 6.9 dB SPL, resulting in the minimum sample size of 28 participants. By considering 10% dropout, this study aimed to recruit 31 participants.

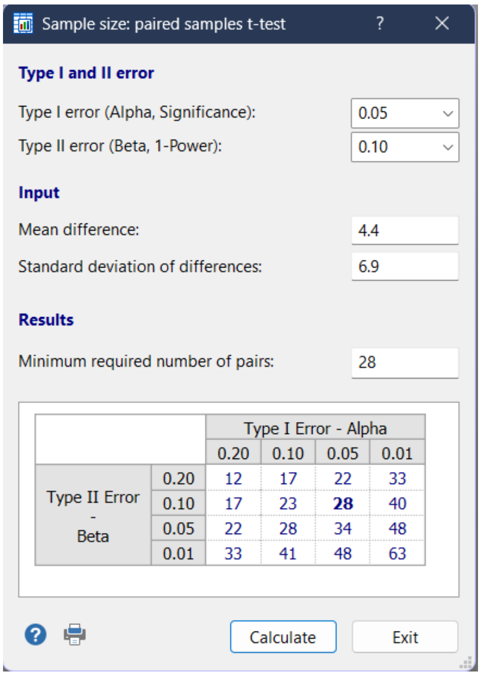


Figure 3.1: MedCalc® Statistical Software (version 23.0.8)

3. 6 Sampling Method and Subject Recruitment

The participant in this study was randomly selected from the undergraduate student population, ensuring equal representation of the both male and female students.

3.7 Research Tool

1. Otoscope (Welch Allyn 3.5v)
2. Tympanometer (GSI Tympstar pro)
3. Audiometer (Grason-Stadler GDI 61 Clinical Two-Channel)
4. TDH-39 Headphones
5. Sentiero Advanced - DPOAE
6. OAE Ear Tips
7. Stopwatch
8. Sound level meter (SLM)
9. Laptop with Audacity software
10. Speaker

3.8 Data Collection Method

Approximately around 45 minutes was required to collect data from both the right and left ear for each participant. Detailed explanation regarding data collection procedure for this study are as below:

1. History Taking:

   In order to conduct effective research in participants with normal hearing, it is important to collect detailed participant histories prior to the study. This process involved gathering information such as age, school/course, hearing status, medical history and any history of otological conditions. Collecting this information is crucial for identifying and excluding confounding factors that could affect the reliability of DPOAE results.

2. Hearing Screening

All subjects were screened to determine their eligibility for the study and the instructions and purpose of each clinical test were explained clearly beforehand. This data collection began with an otoscopy examination to check the ear canal and tympanic membrane to ensure accurate DPOAE measurements. Tympanometry was conducted as well to assess the middle ear function and rule out any pathology. A type A tympanogram using a 226 Hz probe tone would confirm the normal middle ear function, allowing participants to proceed the further testing. Participants then underwent Pure Tone Audiometry (PTA) in both ears to test hearing at 20 dB HL at frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz by using the Hughson-Westlake of obtaining threshold. During the PTA testing, the participants were required to wear headphones and press a button when they hear a tone, allowing for recording air conduction (AC) thresholds. Those with PTA levels over 20 dB HL or abnormal tympanometry results were excluded from the study as these conditions may interfere with DPOAE measurements. Excluded participants were referred to the audiology clinic for further diagnosis and assessments.

3. DPOAE Measurement

Participants who passed the hearing screening were subjected to the DPOAE testing to evaluate cochlear function. The recordings were performed using the Sentiero Advanced device (by Path Medical, Germany), with a probe properly placed in the ear canal to ensure acoustic seal and reduce external noise interference. Before recording, participants received a clear explanation of the procedures to ensure understanding and cooperation.

During the testing, both pure tone (PT) and frequency modulated (FM) stimuli were presented at 55 dB SPL with equal primary tone levels for f_1 and f_2. The DPOAEs were measured across frequencies from 1 kHz to 10 kHz for each stimulus type. The DPOAE test was performed under three listening conditions. The sequence of stimuli would be randomized across the participants and testing began in a quiet environment to establish a baseline for comparison. This then followed by noisy conditions, with white noise introduced at two different levels, i.e., 40 dB SPL and 60 dB SPL generated using Audacity software and played through a speaker. A sound level meter (SLM) was used to ensure the correct noise levels were set before the testing began. The participant remained seated at a fixed position, marked as “X” seated one meter away from the laptop to maintain consistent positioning throughout the procedure.

Each ear was tested separately with DPOAE amplitude and noise floor were recorded at each test frequency. Additionally, the duration of each stimulus type was also recorded to identify which testing method was faster using a dedicated stopwatch. Separate recordings were made for both ears under each listening condition. Finally, the results from the two stimuli were compared.

Figure 3.2: The method of conducting DPOAE testing

3.9 Data Analysis

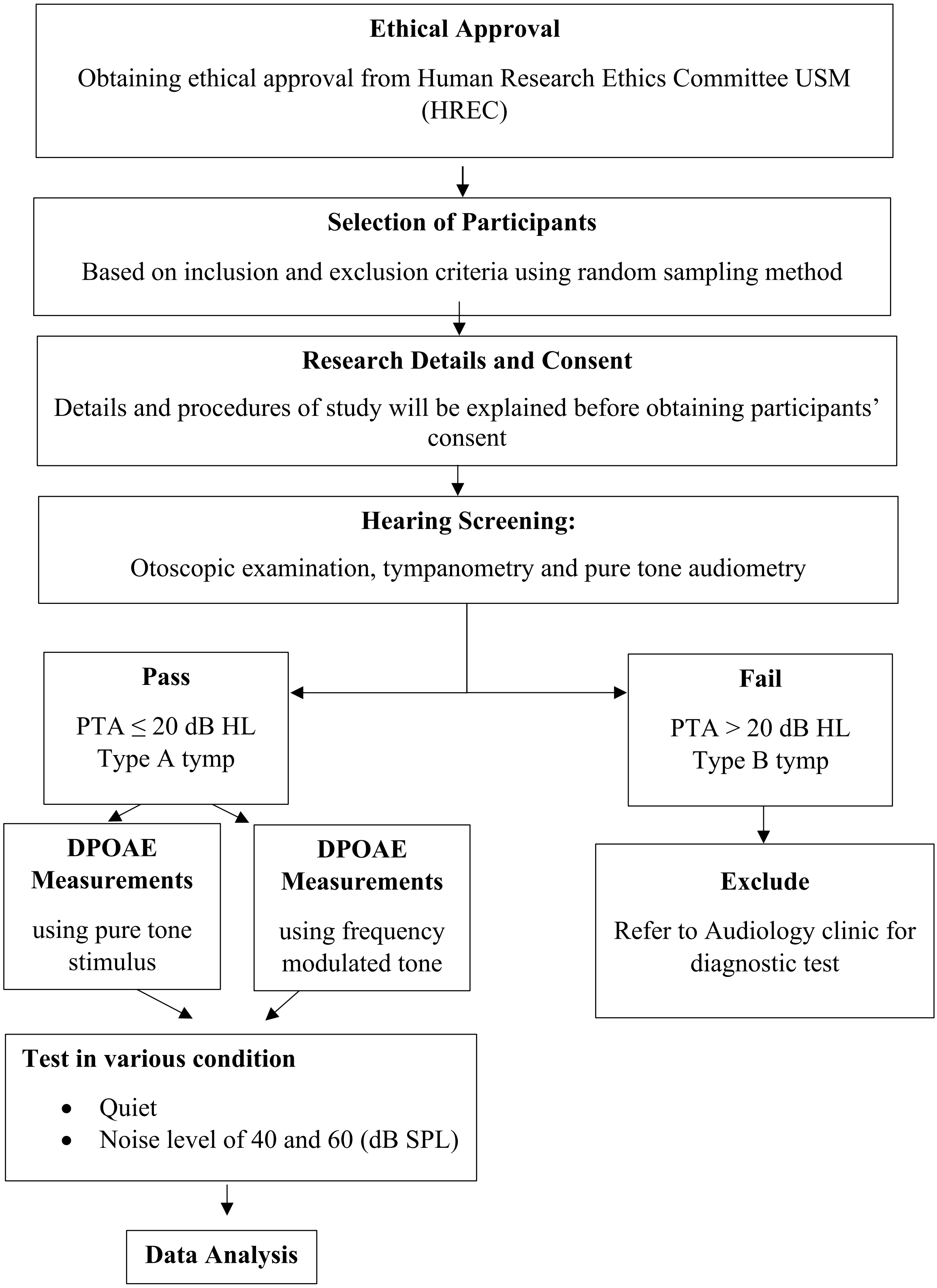
The data collected were analysed using the JASP software (version 0.18.3). The amplitude, signal-to-noise-ratio (SNR) and test duration of DPOAE responses from both right and left ears were documented for each participant. The Shapiro-Wilk test was used to assess the normality of the data distribution. For each condition, the paired t-test (or the Wilcoxon signed rank test if the data are not normally distributed) would be used to compare DPOAE results (amplitude, SNR and test duration) between pure tones and frequency modulated tones.

3.10 Ethical Approval

This study was reviewed and approved by the Human Research Ethics Committee of Universiti Sains Malaysia (HREC-USM) under JEPeM Code: USM/JEPeM/KK/24121125 before starting the data collection. All participants were given a research information sheet that explained the tittle, purpose, steps involved, eligibility requirements, possible benefits and contact details. After the study was clearly explained, they were also given a consent form to sign. Taking part in the study was completely voluntary. The research findings were free from any conflicts of interest, including those involving money, property, or personal gain. Participants who declined to participate or left the study at any point would face no repercussions. Unless disclosure was mandated by law, the supervisor was the only person to receive access to all of the personal information and data was kept private. Only the authorized team members of the researcher had access to all original records. Information sheet and consent form are shown in the Appendices.

3.11 Study Flow Chart

Figure 3.3 illustrates the flowchart of this study



CHAPTER 4

RESULTS

4.1 Demographic Data

Thirty-two participants with normal hearing, aged between 20 to 25 years old were randomly recruited among USM for this study. The age range, mean, and standard deviation (SD) of the participants are illustrated in Table 4.1 and Figure 4.1.

Table 4.1 Age range, mean and SD of participants in this study

Range (year old)	21 - 24
Mean (year old)	22.59
Standard Deviation (year old)	0.95

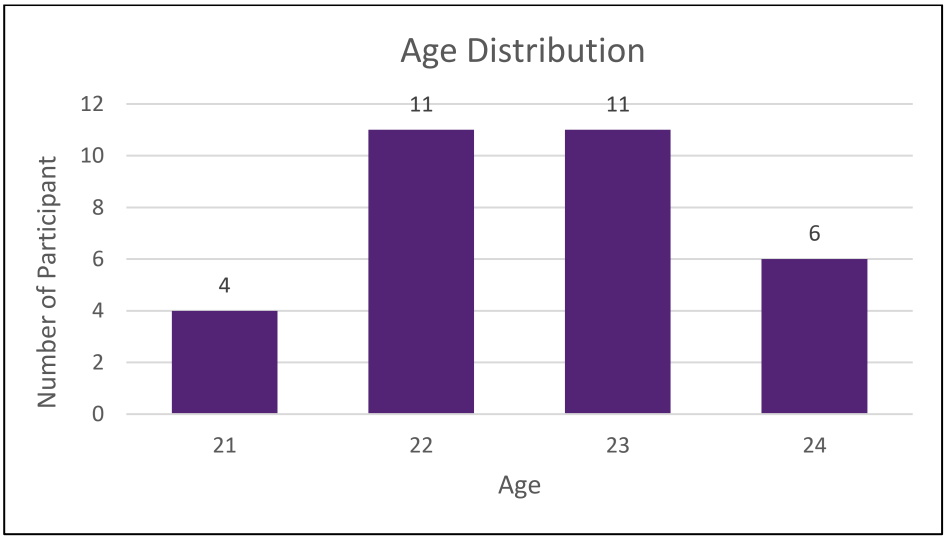


Figure 4.1: Distribution of participants' age distribution

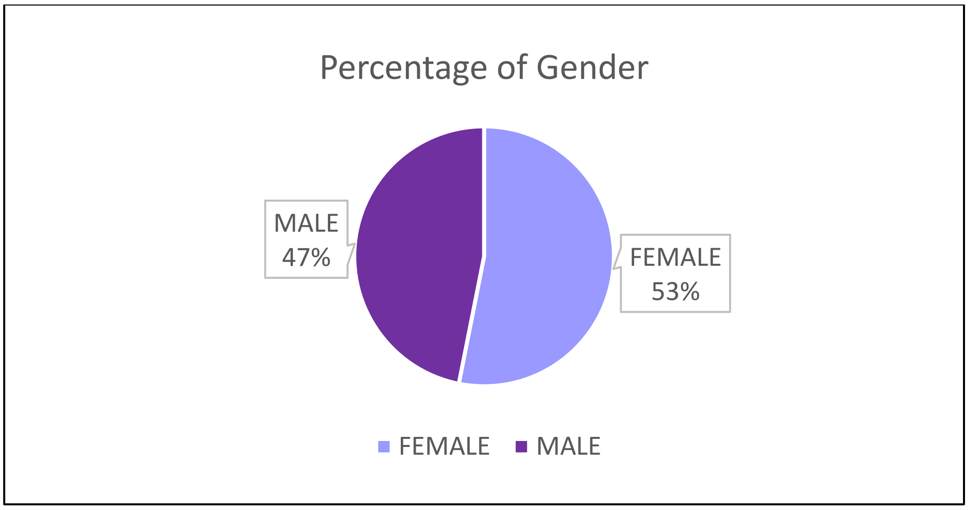


Figure 4.2: Gender distribution among the participants

Among these 32 participants, there are 47% male (n=15) and 53% female (n=17) as shown in Figure 4.2.

4.2 Performance of DPOAE when elicited by Pure Tones and Frequency Modulated Tones Across Conditions

The normality of the DPOAE data was assessed using the Shapiro-Wilk test, which indicated that the date were not normally distributed. Statistical significance was determined using the Wilcoxon Signed-Rank test, a non-parametric test since the data were not normally distributed ($p < 0.05$).

4.2.1 Quiet Condition

4.2.1.1 Signal to Noise Ratio (SNR)

The mean, median, standard deviation (SD), and interquartile range (IQR) of DPOAE SNR values were calculated for PT and FM across frequencies tested from 1 kHz to 10 kHz in the quiet condition, as presented in Table 4.1. The result showed that PT stimuli produced significantly higher median SNR values than FM stimuli (Figure 4.3). Specifically, at 2 kHz, 3 kHz, 4 kHz, 5 kHz, 6 kHz, 7 kHz, 8 kHz and 10 kHz, the difference was statistically significant ($p < 0.05$), favouring PT. The largest difference was found at 7 kHz where the median SNR for PT showed 22.08 dB SPL compared to 19.3 dB SPL for FM stimuli. Although PT at 1 kHz a higher median SNR (16.25 dB SPL) than FM (15.53 25 dB SPL), the difference was not statistically significant ($p = 0.052$). In contrast, at 9 kHz FM stimuli showed significantly higher median SNR than PT (16.03 dB SPL vs 14.93 dB SPL, $p = 0.002$), which was the only frequency where FM resulted in higher SNR values than PT. Overall, PT stimuli generally outperformed FM in enhancing DPOAE SNR across frequencies, FM demonstrated better performance only at 9 kHz.

Table 4.2: Mean, median, standard deviation (SD), interquartile range (IQR) and statistical significance of SNR for PT and FM tones in the quiet condition

Frequency (kHz)	**Pure Tones**		**Frequency Modulated Tones**		**Mean difference**	**P value**
	Mean (SD) (dB SPL)	**Median (IQR) (dB SPL)**	**Mean (SD) (dB SPL)**	**Median (IQR) (dB SPL)**		
1	14.71 (5.65)	16.25 (7.24)	13.89 (6.14)	15.53 (7.73)	0.81	0.052
2	20.22 (4.16)	21.53 (5.35)	18.88 (4.35)	19.88 (6.79)	1.34	<0.001*

3	18.95 (4.95)	20.03 (5.83)	17.26 (4.59)	18.4 (5.26)	1.69	<0.001*
4	20.86 (3.98)	22.23 (4.98)	20.07 (12.16)	19.7 (4.15)	0.79	<0.001*
5	22.66 (3.33)	23.73 (2.49)	20.97 (3.16)	21.93 (2.44)	1.69	<0.001*
6	23.21 (3.51)	24.43 (2.14)	22.50 (3.68)	23.75 (2.73)	0.71	0.001*
7	20.44 (5.86)	22.08 (5.54)	17.99 (5.23)	19.3 (3.85)	2.44	<0.001*
8	17.81 (7.10)	20.75 (11.21)	16.77 (6.65)	19.13 (9.76)	1.04	0.005*
9	12.65 (8.11)	14.93 (12.03)	14.95 (7.35)	16.03 (10.59)	-2.30	0.002*
10	17.31 (6.40)	19.13 (6.46)	16.20 (5.95)	17.98 (8.64)	1.12	0.001*

*Significant at $p < 0.05$

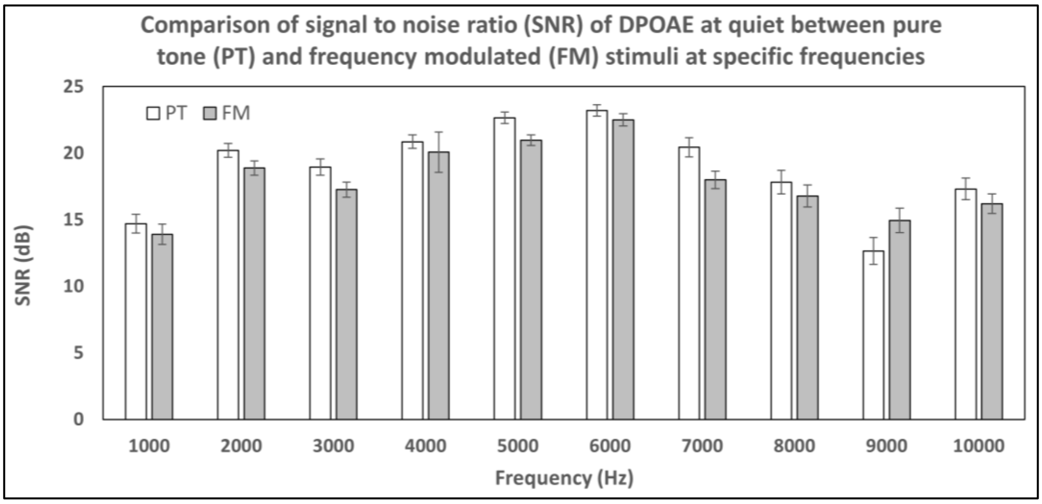


Figure 4.3: Comparison of mean SNR of DPOAE at quiet between PT and FM stimuli at specific frequencies

4.2.1.2 Amplitude

The mean, median, SD and IQR of DPOAE amplitude values were calculated for PT and FM across frequencies tested from 1 kHz to 10 kHz in the quiet condition, as presented in Table 4.2. Based on the median values, PT stimuli elicited higher amplitudes than FM stimuli at most frequencies. Statistically significant differences were observed at 4 kHz and 5 kHz ($p < 0.001$), where the median amplitudes for PT (13.50 dB SPL and 14.98 dB SPL) respectively. This was notably higher than FM (13.05 dB SPL and 14.30 dB SPL) respectively. Meanwhile at 1 kHz, 2 kHz and 3 kHz, 7 kHz and 10 kHz the PT amplitudes were higher than FM but the differences were not statistically significant ($p > 0.05$). In contrast, at 6 kHz, 8 kHz and 9 kHz where FM stimuli produced slightly higher median amplitudes than PT, but these differences were also not significant ($p > 0.05$).

Table 4.3: Mean, median, standard deviation (SD), interquartile range (IQR) and statistical significance of amplitude for PT and FM tones in the quiet condition

Frequency (kHz)	Pure Tones		Frequency Modulated Tones		Mean difference	P value
	Mean (SD) (dB SPL)	Median (IQR) (dB SPL)	Mean (SD) (dB SPL)	Median (IQR) (dB SPL)		
1	8.30 (6.49)	8.73 (7.36)	7.88 (6.91)	8.55 (9.03)	0.42	0.247
2	10.92 (5.89)	11.30 (9.18)	10.55 (6.28)	11.33 (8.80)	0.37	0.095
3	8.82 (5.17)	9.50 (7.09)	8.02 (6.09)	8.35 (7.39)	0.80	0.136
4	14.68 (10.95)	13.50 (7.95)	12.60 (6.81)	13.05 (8.80)	2.07	<0.001*
5	13.98 (6.41)	14.98 (6.63)	13.16 (6.44)	14.30 (8.06)	0.82	<0.001*
6	11.17 (5.97)	13.08 (7.26)	11.55 (7.21)	13.38 (7.35)	-0.38	0.944

7	5.51 (8.28)	6.00 (9.68)	5.00 (8.64)	5.18 (11.56)	0.51	0.154
8	1.37 (9.40)	3.08 (14.08)	1.65 (9.93)	4.18 (14.56)	-0.28	0.101
9	-1.40 (9.23)	0.55 (12.94)	-0.79 (9.19)	-0.45 (13.51)	-0.61	0.521
10	1.64 (7.85)	3.05 (8.61)	1.61 (7.88)	2.28 (12.10)	0.03	0.691

*Significant at $p < 0.05$

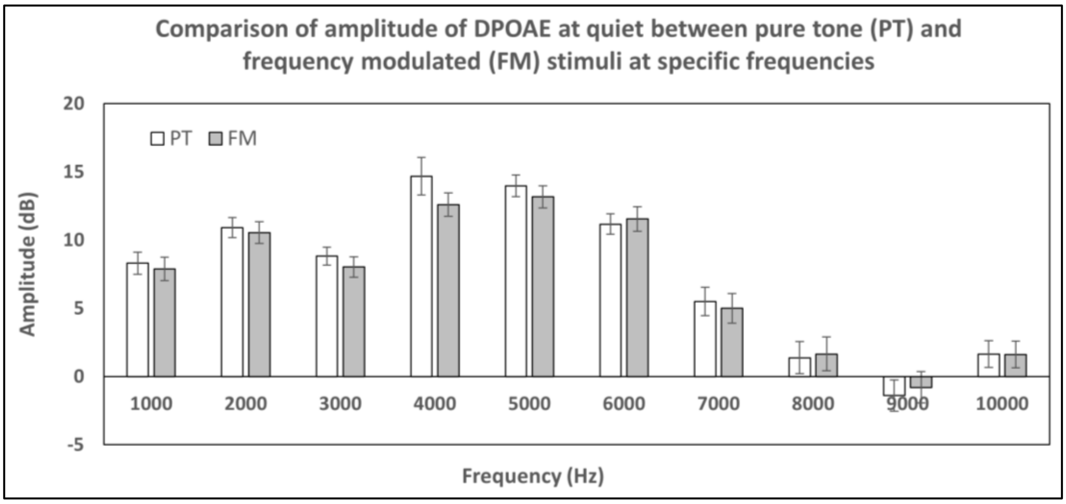


Figure 4.4: Comparison of mean amplitude of DPOAE in the quiet condition between PT and FM stimuli at specific frequencies

4.2.1.3 Duration

As presented in Table 4.3, the DPOAE response duration across frequencies from 1 kHz to 10 kHz was significantly longer for FM stimuli compared to PT stimuli in the quiet condition. The FM stimuli recorded a median duration of 48.5 s, whereas the PT stimuli showed a shorter median duration of 38 s. This difference was statistically significant ($p < 0.001$), indicating that FM stimuli generally required a longer time to complete DPOAE measurements in quiet conditions as shown in Figure 4.5.

Table 4.4: Mean, median, standard deviation (SD), interquartile range (IQR) and statistical significance of duration for PT and FM stimuli in the quiet condition

Frequency (kHz)	**Pure Tones**		**Frequency Modulated Tones**		**Mean difference**	**P value**
	Mean (SD) (dB SPL)	**Median (IQR) (dB SPL)**	**Mean (SD) (dB SPL)**	**Median (IQR) (dB SPL)**		
1 - 10	38.41 (2.33)	38 (1)	49.31 (2.55)	48.50 (2)	10.91	<0.001*

*Significant at $p < 0.05$