Jurnal Teknokes
International: Rapid Review: Open Access Journal **Vol. 17, No. 4, December 2024, pp. 184-189** **e-ISSN 2407-8964; p-ISSN 1907-7904**

RESEARCH PAPER OPEN ACCES
Manuscript received September 18, 2024; accepted October 12, 2024; date of publication December 25, 2024
Digital Object Identifier (DOI): https://doi.org/10.35882/teknokes.v17i4.8

How to cite: Atmi Dwi Jayanti, Andjar Pudji , and M. Ridha Mak'ruf, "Pure-tone Audiometry: A Threshold-Based Approach to Hearing Loss Detection, Jurnal Teknokes, Vol. 17, No. 4, December 2024, pp. 184-189.

Pure-tone Audiometry: A Threshold-Based Approach to Hearing Loss Detection

Atmi Dwi Jayanti, Andjar Pudji, and M. Ridha Mak'ruf
Department of Electromedical Engineering, Poltekkes Kemenkes, Surabaya, Indonesia.
Corresponding author: Atmi Dwi Jayanti (e-mail: atmidj94@gmail.com)

ABSTRACT Hearing loss is a condition where the normal hearing process is impaired in one or both ears. Based on the hearing threshold, hearing loss can be classified as mild, moderate, severe, or very severe. To diagnose hearing loss, an audiometry examination is commonly used to assess hearing function and determine the degree of hearing impairment. However, differences in measurement accuracy between manual methods and conventional audiometry devices may exist and need to be evaluated. This study aims to identify hearing loss by applying hearing thresholds using pure-tone audiometry and to compare the results of a custom audiometry module with conventional audiometry equipment. Hearing loss was assessed using a pure-tone audiometry module in both manual and automatic modes. The results were compared with a standard audiometry device. The comparison focused on the hearing threshold values obtained for both the left and right ears. The study revealed differences in average hearing threshold values between the module and the conventional audiometry in the left ear was between 1.00 dB to 5.00 dB (1.00% to 20.00%) and the right ear was between 1.25 dB to 3.75 dB (4.2% to 30 %).The custom audiometry module produced hearing threshold results consistent with the classification of hearing loss degrees obtained from the conventional audiometry device. This indicates that the module is a dependable tool for identifying hearing loss, maintaining consistency in hearing loss classification despite minor numerical differences in threshold values.

INDEX TERMS Hearing Loss, Degree of Deafness, Hearing Threshold, Pure-Tone Audiometry.

I. INTRODUCTION

Hearing loss is a condition of interference with the normal hearing process in one or both ears [1]. If there is hearing loss, there will be problems during the process of receiving information and communication[2] . Sounds cannot be heard clearly or even people with hearing loss cannot hear at all, which is called hearing loss. The ear is an organ that works as a receiver and conductor of sound and sound. Which is where the ear has the anatomy of the outer ear, middle ear, and inner ear [3]. Hearing loss conditions based on hearing thresholds are hearing loss with mild, moderate, severe and very severe degrees [4]. Apart from the degree, hearing loss is also divided into three types including conductive hearing loss, sensorineural hearing loss, and mixed hearing loss [5].

Hearing loss is influenced by several factors, including age[6], having a disease (diabetes mellitus, hypertension, heart) [7], genetic factors in newborns[8], exposure to noisy machine sounds[9]. Hearing loss not only occurs in adults but also in infants and children. Symptoms of hearing loss in adults in general are experiencing a decrease in sound during the hearing process, such as sounds that are heard sounding smaller, ringing in the ears or what is called tinnitus. However, symptoms of hearing loss in infants and children include not being surprised when hearing loud sounds and not responding when called or not looking for the source of the sound. In infants, it will have an impact on the child's growth and development. Because it will be difficult to pronounce words and impact the child will experience speech delay or speech delay [10][11]. So to avoid this, early examination can be done. To check the presence or absence of hearing loss in newborn babies, it can be done using an OAE (Oto Acoustic Emission) tool which can function to check for abnormalities in the clokea [12][13]. There are several examinations that can be done to get a diagnosis of hearing loss, including using the tuning fork test, tests using audiometry (pure tone audiometry and speech audiometry)[14][15], using tympanometry [16]. However, to determine the frequency range and intensity of sounds that can be heard, namely with audiometric tests. Audiometry is a tool that serves to determine the hearing function and the degree of deafness experienced by the patient [17]. Audiometry has two examination techniques, namely speech audiometry and pure tone audiometry[18][19]. Speech audiometry functions for the ability to understand audible speech . While pure tone audiometry is the ability to hear sounds or tones given by the operator [20]. This audiometry examination is carried out by means of the patient being paired with earphones in the ear and will be given a voice by the operator and the patient will respond if he hears the sound and the examination continues until the patient does not hear or does not respond [21].

In 2013, Anton Ratrianto and colleagues conducted a study focused on designing and developing a microcontroller-based digital audiometer using the ATmega 8535. Their research covered the tool's design, fabrication, and functional testing, demonstrating its capability to generate diverse frequencies and sound intensities that comply with audiometric standards. The measurement outcomes were presented visually through an audiogram. In 2017, Jessica Van Tonder and colleagues conducted a study aimed at evaluating the validity of a sound threshold test using a smartphone application, hearTest, by comparing its performance with traditional audiometry methods. The research also explored the time efficiency of conducting examinations with the application compared to conventional audiometric techniques [22]. In 2019, Fei Chen and colleagues investigated a smartphone-based hearing self-assessment system that utilizes audiometry to detect hearing loss across a range of frequencies in both ears. Their system demonstrated the ability to deliver fast and accurate examination results[23]. Seung Yeol Lee, et al evaluating the Precision and Consistency of Audiometry through Mobile Applications for Hearing Assessment [24]. The study contains testing of smartphone-based applications for hearing evaluation by making comparisons with conventional pure audiometry tests. Hearing threshold tests are measured using smartphone application-based audiometry tests and the results are compared with conventional pure audiometry tests.

In 2023, Aris I. Giotakis and colleagues conducted a study to assess the advantages of air-conduction pure-tone audiometry as a screening method for hearing loss compared to the visual analog score (VAS)[25]. This study aims to evaluate the benefits of air-conduction ear audiometry as a screening method for hearing loss over the visual analog score. Examination using Modified Pure-Tone Audiometry (mPTA) is better than the VAS score for screening hearing loss in primary health care because it is more sensitive and fast. Based on the weaknesses and strengths of previous research, the author wants to develop a tool to identify hearing disorders using Pure-Tone Audiometry to make it easier for doctors to and audiologists to identify hearing loss faster and more accurately.

II. MATERIALS AND METHODS

Hearing involves the senses within the ear, which is an important organ for auditory function and balance mechanisms. Audiometry examination is a test conducted to measure hearing ability. Audiometry has two examination techniques including: Pure-Tone Audiometry: The pure tone examination uses frequencies of 250 Hz, 500 Hz, 1,000 Hz, 2,000 Hz, 4,000 Hz, 8,000 Hz. Patients can respond by pressing the button on the device if they hear the sound on the headphones. In determining the degree of deafness or degree of hearing loss can be seen in the audiogram. Speech Audiometry: The examination of speech tone is to determine the ability to hear and understand speech given through headphones. In this examination the patient responds by imitating the words that are listened to [9]. This examination aims to determine hearing loss in conductive and sensorineural organs. One of the examinations used to detect the type of hearing loss and determine the degree of hearing loss is audiometric examination [26]. ESP 32: The ESP32 microcontroller is a microcontroller equipped with a very complete chip with a processor, memory and GPIO access. ESP32 is connected by Wi-Fi and ESP32 has 30 GPIO and 36 GPIO with the same function. However, the 30 GPIO version is more widely chosen because it has 2 GND pins. The ESP32 board has a USB to UART interface so it is easy to program with application development programs such as Arduino IDE [27]. TFT LCD: TFT (Thin Film Transistor) LCDs are widely used to display high-quality visuals on various devices. This technology is widely found in cell phones, laptops, and everyday electronic devices. In addition, TFT LCDs are often used in automotive systems, medical devices, and industrial applications to provide clear and accurate data displays. Its advantages include sharp colors, fast response time, and adaptability to various needs.

A. Data Collection

Data collection was carried out by testing the audiometry module tool to respondents. There were 8 respondents with different ages ranging from 29 years old to 58 years old. Testing was carried out using pure tones with varying frequencies, namely between 125Hz-8000Hz. Respondents will respond to the intensity of the sound given starting from 60 dB to the intensity of the sound that can be heard by the respondent. Recording the results on the module will be recorded in the form of an audiogram showing the respondent's hearing threshold at each frequency. Descriptive analysis in this case is to calculate the average value of the hearing threshold or called the Pure Tone Average (PTA) which is used to determine the degree of hearing loss. The calculation of the average hearing threshold refers to or uses the ISO 8253-1: 2010 standard on audiometric testing methods using air conductance and bone conductance including the provisions of Pure Tone Audiometry testing. Average hearing threshold measurements use frequencies of 500Hz, 1000Hz, 2000Hz, and 4000Hz. The hearing threshold value (in dB HL) is obtained from the audiometry results recorded on the audiogram at each frequency. Then the hearing loss was identified (normal, mild, moderate, severe, and very severe).

B. Data Processing

The resulting data set will form a graph Where this measurement requires ESP32 as a microcontroller with C language programming. The ESP32 board has a USB to UART interface so it is easily programmed with application development programs such as Arduino IDE. From ESP32, it enters the signal generator circuit which functions as a sine signal generator whose frequency can be adjusted through the program. Then enter the digital attenuator/potentiator circuit used to adjust the sound intensity level (dB) and enter the amplifier to be amplified so that the sound can be heard in the right headphone and left headphone. Then the audiogram results can be displayed on the TFT LCD and can be printed with a portable printer Based on FIGURE 1.

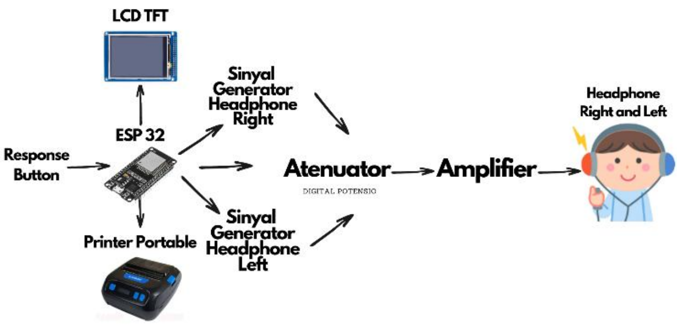

FIGURE 1 **Block diagram of Identification of Hearing Loss Based on Hearing Thresholds Using Pure-Tone Audiometry.**

The calculation of the average value to determine the inspection result based on EQUATION 1:

$$\text{Avarage: } \frac{value\ at\ 500Hz + value\ at\ 1000Hz + value\ at\ 2000Hz + value\ at\ 4000Hz}{4} \quad (1)$$

After the PTA value is calculated, compare the result with the hearing loss degree classification TABLE 1:

TABLE 1 **Classification of Hearing Loss Degree**

No	Sound Intensity (dB)	Category
1	0-25 dB	Normal
2	26-40 dB	Mild
3	41-55 dB	Moderate
4	56-70 dB	Moderate to Extreme
5	71-90 dB	Extreme

TABLE 1 Is a classification of hearing loss based on sound intensity thresholds measured in decibels (dB). The table classifies hearing loss based on sound intensity in decibels (dB), ranging from normal (0–25 dB) to extreme (71–90 dB), with increasing severity as follows: mild (26–40 dB), moderate (41–55 dB), and moderate to extreme (56–70 dB), indicating the level of impairment and guiding appropriate interventions.

III. RESULT

A. *Hearing Threshold Measurement*

The study involved eight respondents to compare hearing threshold measurements between the custom module and standard audiometry. Measurements were conducted across frequencies ranging from 125Hz to 8000Hz, starting at 60 dB to a sound intensity that can be heard by the respondent. Recording of results on the module will be recorded in the form of an audiogram and the average hearing threshold value used to determine the degree of hearing loss.

B. *Accuracy*

TABLE 2 Presents the average hearing threshold results for the left and right ears, along with the differences between the module and audiometry, expressed in decibels (dB) and percentages. The module demonstrated high accuracy, with most average hearing threshold differences being below 5 dB and percentage differences below 30%. Across all grades of hearing loss, the module consistently identified levels of hearing loss, ranging from normal to extreme, with results consistent with standard audiometric measurements. This demonstrates that the module is not only accurate in its measurement of average hearing thresholds, but also reliable in detecting levels of hearing loss across a range of clinical categories.

TABLE 2 **Results of Measurements using the Module and Audiometry.**

Respondent	Ear	Average Hearing Treshold Result (dB)		Average Hearing Threshold Difference (dB)	Percentage Difference Value (%)	Hearing Loss (Degree of Deafness)
		Module	Audiometry			
1	L	35.0	32.5	2.50	7.1	Mild
	R	17.5	15.0	2.50	14.3	Normal
2	L	17.5	15.0	2.50	14.3	Normal
	R	17.5	15.0	2.50	14.3	Normal
3	L	27.5	26.5	1.00	3.6	Mild
	R	30.0	26.5	3.50	11.7	Mild
4	L	15.0	12.5	2.50	16.7	Normal
	R	12.5	8.75	3.75	30.0	Normal
5	L	25.0	20.0	5.00	20	Normal
	R	15.0	13.75	1.25	8.3	Normal
6	L	17.5	15.0	2.50	14.3	Normal
	R	25.0	22.5	2.50	10	Normal
7	L	100	98.75	1.25	1.3	Extreme
	R	30.0	28.75	1.25	4.2	Mild
8	L	52.5	48.75	3.75	7.1	Moderate
	R	52.5	48.75	3.75	7.1	Moderate

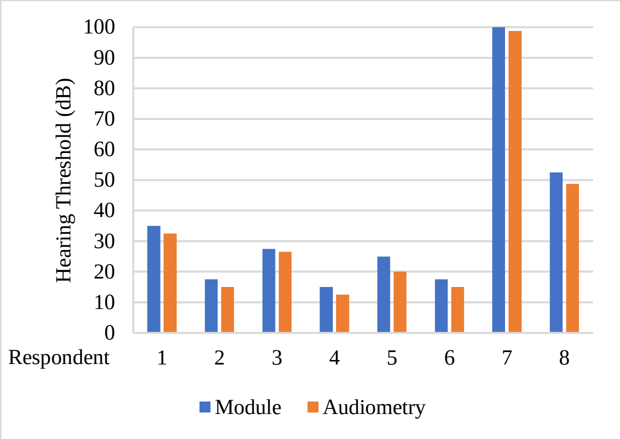

FIGURE 2. **Graphic of the average hearing threshold result between the module and audiometry for the left ear.**

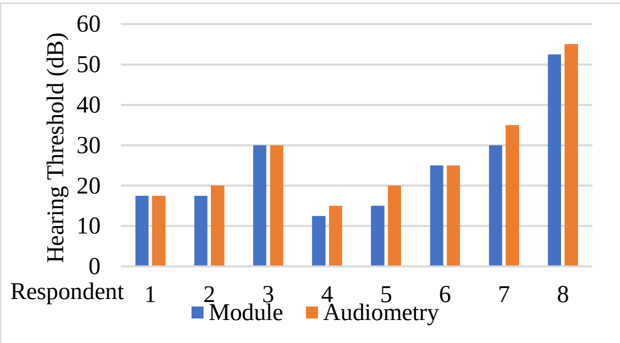

FIGURE 3. **Graphic of the average hearing threshold result between the module and audiometry for the right ear.**

FIGURE 2. and FIGURE 3. Show graphic results of the average hearing threshold measurements using the module and audiometry for the left and right ears. In general, both methods produce similar values, with an average difference of less than 5 dB, which is within the limits of clinical tolerance. In the left ear, the module recorded a slightly higher hearing threshold than audiometry, while in the right ear, the variation was more diverse but remained clinically consistent.

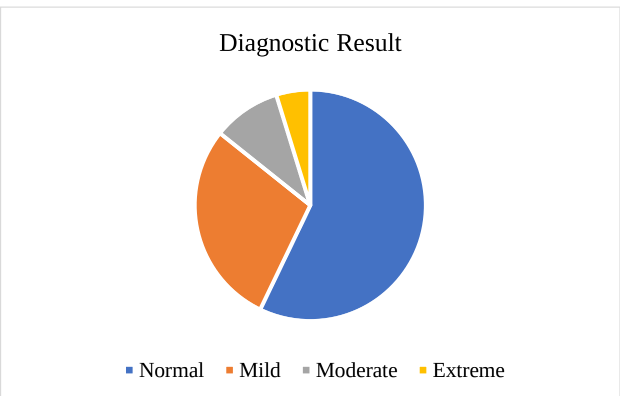

FIGURE 4. **Distribution of Hearing Loss Levels Based on Audiometry Module Diagnosis**

FIGURE 4. Show the majority of respondents diagnosed with mild to extreme hearing loss have an average threshold difference value in the range of 1.0–3.75 dB, which is still within the accuracy limits of the device. With this accuracy, the audiometry module can be used as an efficient alternative for early detection of hearing loss, providing results consistent with conventional audiometry devices. Although the module demonstrated high accuracy, some differences were observed during comparison with standard audiometric results, such as in the right ear of Respondent 4, where the percentage difference reached 30%. These errors may be caused by factors such as differences in calibration between the module and standard audiometric devices, environmental conditions such as background noise, or respondent-specific factors such as fatigue during long testing sessions. Although these differences remain within clinically acceptable limits, these results highlight the need for improvement in several aspects, including more accurate calibration, better algorithm design, and tighter environmental controls. With improvements in these areas and expansion of the study to a larger sample population, the module's reliability and accuracy could be further improved, strengthening its potential as a clinical tool for the diagnosis of hearing loss.

IV. DISCUSSION

This study demonstrates that the developed module delivers accurate and reliable hearing threshold measurements, closely matching the results obtained from standard audiometry methods. On average, the differences in threshold values between the module and conventional audiometry were less than 5 dB, with percentage differences below 20%. These findings confirm that the module provides precision comparable to established audiometric devices, highlighting its potential as an effective tool for hearing assessment. The module's accuracy and resolution suggest it could serve as a cost-effective and accessible option for hearing assessments, especially in resource-constrained environments. The minimal discrepancies in threshold measurements validate its ability to assess hearing loss across various levels of severity. Furthermore, the module's effectiveness in classifying hearing conditions, from normal to very severe loss, underscores its clinical utility. These results are consistent with earlier studies on portable audiometric devices, such as the work by Karavaev and Pavlov (2024) [28] which introduced a similar device for hearing assessment. Their research demonstrated precise threshold measurements and portability for diagnostic purposes. While both devices focus on accuracy and mobility, the module in this study uses 10 dB increments for sound intensity adjustments, a resolution slightly lower than Karavaev and Pavlov's system, which supports finer adjustments. The device developed by Karavaev and Pavlov incorporates advanced electronic features for precise measurement of pure-tone audiometry thresholds and additional functionalities like pitch differentiation. While their system focuses on specialized technology for high-precision assessments, the module in this study emphasizes affordability and ease of use, making it particularly well-suited for widespread implementation in diverse and resource-limited settings. While the pitch measurement and electronic data storage features in Karavaev and Pavlov's system highlight opportunities for further enhancement, the current module offers a strong foundation and demonstrates significant potential as an accessible and effective hearing assessment tool.

To address these challenges, future improvements should focus on:

1. Enhancing Precision: Enable finer sound intensity adjustments for greater accuracy.
2. Adding Digital Features: Include options to store audiograms and input patient information.
3. Improving Compatibility: Integrate with electronic medical record systems.
4. Expanding Validation: Conduct larger studies with diverse populations to ensure reliability.

The module’s portability and affordability make it ideal for remote or underserved areas. By improving its precision and incorporating digital tools, the module could play a key role in reducing untreated hearing loss. By building on prior research and addressing its limitations, this study underscores the importance of affordable, reliable, and accessible audiometric devices. The findings provide a foundation for further innovation in tackling global hearing health challenges..

V. CONCLUSION

This study aims to identify hearing loss by applying hearing thresholds using pure-tone audiometry and to compare the results of a custom audiometry module with conventional audiometry devices. The study also evaluate the module’s effectiveness as a portable and cost-efficient alternative for hearing assessment. With an average threshold error of ±2.5 dB, the module maintains consistent classification of hearing loss levels, ensuring reliability in diagnosing various degrees of hearing impairment. Its features, including frequency and intensity adjustments, Bluetooth-enabled printing, and visual audiogram display, enhance usability and practicality for field applications. These findings highlight the potential of the module to improve accessibility to hearing assessments, particularly in resource-limited or remote areas. Future developments should focus on enhancing measurement precision, integrating advanced features, and conducting broader field trials to further validate its clinical utility and expand its applications in audiological diagnostics.

REFERENCES

[1] F. Lintong, “Gangguan Pendengaran Akibat Bising,” *J. Biomedik*, vol. 1, no. 2, 2013, doi: 10.35790/jbm.1.2.2009.815.

[2] T. Husni and Thursina, “Pola Gangguan Pendengaran Di Poliklinik Telinga Hidung Tenggorok Kepala Leher (Tht-Kl) Rsud Dr. Zainoel Abidin Banda Aceh Berdasarkan Audiometri,” *J. Kedokt. Syiah Kuala*, vol. 12, no. 1, pp. 16–22, 2012.

[3] E. N. Amany, R. Rosalinda, J. Munilson, and Y. Edward, “Peran Audiometri Tutur pada Otitis Media Supuratif Kronis,” *J. Otorinolaringol. Kepala dan Leher Indones.*, vol. 1, no. 1, pp. 67–82, 2023, doi: 10.25077/jokli.v1i1.8.

[4] H. Liu, X. Fu, M. Li, and S. Wang, “Comparisons of air-conduction hearing thresholds between manual and automated methods in a commercial audiometer,” *Front. Neurosci.*, vol. 17, no. December, pp. 1–8, 2023, doi: 10.3389/fnins.2023.1292395.

[5] S. Rahman, F. Azman, and Rahmadona, “Deteksi dan Solusi Gangguan Pendengaran dalam Meningkatkan Kualitas Hidup,” *ResearchGate*, no. February, pp. 21–23, 2015, [Online]. Available: https://www.researchgate.net/publication/274193408_Deteksi_dan_Solusi_Gangguan_Pendengaran

[6] T. Dewi and E. P. Setiawan, “Gambaran audiometri pada penderita otitis media supuratif kronis di poliklinik THT-KL RSUP Sanglah tahun 2016-2017,” *Medicina (B. Aires).*, vol. 50, no. 3, pp. 433–437, 2019, doi: 10.15562/medicina.v50i3.609.

[7] A. Limardjo, A. Kadir, R. Djamin, and F. Perkasa, “Analisis gangguan pendengaran pada penderita Diabetes Melitus Tipe-2 berdasarkan pemeriksaan Audiometri Nada Murni dan Audiometri Tutur Analysis of Hearing Impairment on Type-2 Diabetes Mellitus based on Pure Tone Audiometry and Speech Audiometry Examinat,” *J. Kedokt. Yars.*, vol. 17, no. 3, pp. 192–203, 2009.

[8] R. Aditomo and D. A. Ruspita, “Karakteristik Pasien yang Menjalani Pemeriksaan Brainstem Evoked Response Audiometry (BERA) di RSUP Dr. Kariadi Semarang,” *CoMPHI J. Community Med. Public Heal. Indones. J.*, vol. 2, no. 1, pp. 132–138, 2021, doi: 10.37148/comphijournal.v2i1.25.

[9] A. Latupono, E. Savitri, and A. Kadir, “Audiogram dan Audiometri Tutur pada Lansia dengan Presbikusis,” *J. Ilm. Kesehat.*, vol. 3, no. 3, pp. 177–183, 2021, doi: 10.36590/jika.v3i3.198.

[10] J. Jauhari, “Deteksi Gangguan Pendengaran pada Anak Usia Dini,” *GENIUS Indones. J. Early Child. Educ.*, vol. 1, no. 1, pp. 61–71, 2020, doi: 10.35719/gns.v1i1.8.

[11] R. Andriani, R. Sekartini, R. Suwento, and J. R. Batubara, “Peran Instrumen Modifikasi Tes Daya Dengar sebagai Alat Skrining Gangguan Pendengaran pada Bayi Risiko Tinggi Usia 0-6 Bulan,” *Sari Pediatr.*, vol. 12, no. 3, p. 174, 2016, doi: 10.14238/sp12.3.2010.174-83.

[12] C. R. Kennedy *et al.*, “Otoacoustic emissions and auditory brainstem responses in the newborn,” *Arch. Dis. Child.*, vol. 66, no. 10 SPEC NO, pp. 1124–1129, 1991, doi: 10.1136/adc.66.10_Spec_No.1124.

[13] A. Gulati, P. Sakthivel, I. Singh, and S. Ramji, “The Hearing Status of Preterm Infant’s ≤ 34 Weeks as Revealed by Otoacoustic Emissions (OAE) Screening and Diagnostic Brainstem Evoked Response Audiometry (BERA): A Tertiary Center Experience,” *Indian J. Otolaryngol. Head Neck Surg.*, vol. 74, no. s1, pp. 178–183, 2022, doi: 10.1007/s12070-020-01945-3.

[14] D. W. Swanepoel, S. Mngemane, S. Molemong, H. Mkwanazi, and S. Tutshini, “Hearing assessment-reliability, accuracy, and efficiency of automated audiometry.,” *Telemed. J. E. Health.*, vol. 16, no. 5, pp. 557–563, 2010, doi: 10.1089/tmj.2009.0143.

[15] H. Hiraumi, S. I. Oikawa, K. Shiga, and H. Sato, “Systemic cisplatin increases the number of patients showing positive off-frequency masking audiometry,” *PLoS One*, vol. 18, no. 7 JULY, pp. 1–9, 2023, doi: 10.1371/journal.pone.0287400.

[16] Z. Guo, G. Yu, H. Zhou, X. Wang, Y. Lu, and Q. Meng, “Utilizing True Wireless Stereo Earbuds in Automated Pure-Tone Audiometry,” *Trends Hear.*, vol. 25, no. 381, 2021, doi:

10.1177/23312165211057367.

[17] R. Mandala, A. Kenap, and M. Aleng, "Pengembangan Aplikasi Sistem Pakar Pendiagnosis Gangguan Pendengaran Dan Kelainan Telinga," *Sist. Pakar Diagnosis*, vol. 2007, no. Snati, pp. 79–86, 2007.

[18] A. Ratrianto and A. A. Zahra, "Tingkat Derajat Ketulian Menggunakan Mikrokontroler Atmega 8535," *Transient*, vol. 2, 2017.

[19] K. Kaga, "Audiometry," *Adv. Otorhinolaryngol.*, vol. 75, pp. 20–23, 2014, doi: 10.1159/000350596.

[20] Q. Meng, J. Chen, C. Zhang, J. W. A. Wasmann, D. L. Barbour, and F. G. Zeng, "Editorial: Digital hearing healthcare," *Front. Digit. Heal.*, vol. 4, 2022, doi: 10.3389/fdgth.2022.959761.

[21] X. D. Song, B. M. Wallace, J. R. Gardner, N. M. Ledbetter, K. Q. Weinberger, and D. L. Barbour, "Fast, Continuous Audiogram Estimation Using Machine Learning," *Ear Hear.*, vol. 36, no. 6, pp. e326–e335, 2015, doi: 10.1097/AUD.0000000000000186.

[22] J. Van Tonder, D. W. Swanepoel, F. Mahomed-Asmail, H. Myburgh, and R. H. Eikelboom, "Automated smartphone threshold audiometry: Validity and time efficiency," *J. Am. Acad. Audiol.*, vol. 28, no. 3, pp. 200–208, 2017, doi: 10.3766/jaaa.16002.

[23] F. Chen, S. Wang, J. Li, H. Tan, W. Jia, and Z. Wang, "Smartphone-Based Hearing Self-Assessment System Using Hearing Aids with Fast Audiometry Method," *IEEE Trans. Biomed. Circuits Syst.*, vol. 13, no. 1, pp. 170–179, 2019, doi: 10.1109/TBCAS.2018.2878341.

[24] S. Y. Lee, H. W. Seo, S. M. Jung, S. H. Lee, and J. H. Chung, "Assessing the accuracy and reliability of application-based audiometry for hearing evaluation," *Sci. Rep.*, vol. 14, no. 1, pp. 1–9, 2024, doi: 10.1038/s41598-024-57944-9.

[25] A. I. Giotakis *et al.*, "The Benefit of Air Conduction Pure-Tone Audiometry as a Screening Method for Hearing Loss over the VAS Score," *Diagnostics*, vol. 14, no. 1, pp. 1–11, 2024, doi: 10.3390/diagnostics14010079.

[26] A. Rahayu, E. Suherlan, and A. H. Hassan, "Scoping Review : Gambaran Derajat dan Jenis Gangguan Pendengaran pada Usia Tua," *Pros. Kedokt.*, pp. 616–627, 2021, [Online]. Available: https://karyailmiah.unisba.ac.id/index.php/dokter/article/view/26752

[27] M. N. Nizam, Haris Yuana, and Zunita Wulansari, "Mikrokontroler Esp 32 Sebagai Alat Monitoring Pintu Berbasis Web," *JATI (Jurnal Mhs. Tek. Inform.*, vol. 6, no. 2, pp. 767–772, 2022, doi: 10.36040/jati.v6i2.5713.

[28] V. V Karavaev and A. V Pavlov, "Development of the Device for Human Hearing Assessment," in *2024 IEEE 25th International Conference of Young Professionals in Electron Devices and Materials (EDM)*, IEEE, Jun. 2024, pp. 2160–2163. doi: 10.1109/EDM61683.2024.10615189.