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Digital Pure Tone Audiometer: A Smart and Self-Administered Hearing Test System

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Abstract:

Hearing loss affects over 430 million people globally, with the World Health Organization projecting this figure to rise to 700 million by 2050. Despite its prevalence, access to affordable and accurate diagnostic tools remains limited, particularly in low-resource settings. Traditional audiometry systems rely on complex hardware and proprietary software, limiting their scalability and adaptability. This device reimagines such systems by utilizing open-source technologies to create a user-friendly device. The core problem lies in bridging the gap between affordability and diagnostic accuracy while ensuring compliance with international audiometric standards. The solution integrates a Raspberry Pi with headphones and a touchscreen interface, capable of performing pure-tone audiometry across frequencies (125 Hz–8 kHz) at intensities up to 120 decibel Hearing Level. Key features include automated threshold detection, real-time audiogram visualization, and dual operational modes (manual/auto) to accommodate diverse clinical workflows. The auto mode uses adaptive algorithms to reduce testing time, while the manual mode allows clinicians fine control for unusual cases. The procedures

encompassed iterative prototyping, software development for tone generation and response logging, and rigorous clinical validation. Calibration was performed using a reference sound level meter, while usability metrics (e.g., touch responsiveness, test duration) were quantified through timed trials. Results demonstrated a mean threshold deviation of ± 4 decibel Hearing Level compared to the commercial device. Testing involved 49 participants, including clinicians and patients, to evaluate accuracy, usability, and efficiency. This device underscores the viability of open-source, low-cost solutions in bridging healthcare disparities, offering a scalable model for hearing loss diagnosis.

Keywords: *Audiometric testing, Digital pure tone audiometer, Patient response, Raspberry-pi, Real-time representation, User interface*

INTRODUCTION

Auditory loss is a widespread health issue affecting millions of people across the globe. According to the World Health Organization, around 1.5 billion individuals currently live with some degree of Auditory loss and this figure is expected to rise to over 2.5 billion by 2050 [1]. This progressing problem creates challenges not only for those directly impacted but also for society, as it causes emotional and financial difficulties. It is estimated that untreated hearing impairments result in global financial fatalities amounting to hundreds

of billions of dollars every year, including costs associated to lost productivity and healthcare. This highlights the importance of early diagnosis and intrusion to decrease the long-term consequences of hearing loss. One of the most effective methods accessible for diagnosing hearing loss is pure-tone audiometry. It is stated as the gold standard for evaluating a person's sensitivity to innumerable sound frequencies and figuring out the lowermost decibel levels they can perceive.

The information obtained from pure tone audiometry is crucial for creating successful hearing treatment plans in addition to diagnosis. For those who use hearing aids, audiograms let audiologists adjust devices to each person's unique hearing necessities. Pure tone audiometry is used to evaluate eligibility and establish expectations for post-surgery hearing outcomes in instances that require cochlear implants [2].

Due to financial restrictions, many healthcare amenities find it difficult to purchase the required technology, especially those in underserved or rural locations. The public health problem of untreated hearing loss may deteriorate as a result of this financial restriction, which may prevent early detection and care [3]. For conventional audiometers to function efficiently, specific training is repeatedly needed. If workers are not appropriately skilled, the multifariousness of testing procedures and equipment calibration may result in inconsistent outcomes. Due to the need for experienced staff, audiometric evaluations can only be achieved in a limited number of locations, including community health centres and other non-specialized settings [4].

In order to improve diagnosis accuracy and produce further personalized treatment strategies, the audiometry device and results facilitate by production of vital information on the kind and severity of hearing loss along with other associated diseases, i.e, rheumatoid arthritis [5]. The audiometer helps with consistent audiometric data collection, which is crucial for figuring out the pervasiveness and effects of hearing loss, in addition to its diagnostic benefits. Public health drives and the design of plans to improve hearing health more broadly can both benefit from such data [6]. By reassuring more people to get assessments and take preemptive action, it can endorse improved auditory health in various populations [7].

The project advances audiology and improves user experience by leveraging components such as the Raspberry Pi and IQ Audio DAC (Digital to Analog Converter). This audiometer's adaptability makes it appropriate for use in a variety of settings, such as community health programs, educational institutions, and clinical settings, which ensures that hearing assessments can be carried out in a variety of settings, meeting the demands of various populations. Additionally, this system allows efficient data sharing and communication. The audiometer's original features complement the most recent developments in medical technology. Furthermore, the project can reduce financial problem that untreated hearing loss places on healthcare systems to assist early identification and interference [8].

In 2018, a MATLAB-based audiometry system was developed, using a modified Hughson-Westlake procedure for efficacious detection of hearing thresholds [9]. This design featured a bi-aural audiogram comparator with a GUI (Graphic User Interface) that allows a clinician to compare bilateral audiograms. In 2020, a significant leap toward self-administered hearing assessments was represented by the open-source Python audiometer. Constructed on a Raspberry Pi 3 B+, this device automated the Hughson-Westlake protocol, allowing users to conduct audiometric tests independently [10]. The result was an audiogram, in a format that showed the results of the assessment and allowed the kind of data sorting and organizing that enhanced the ability to make use of the results. A model was introduced in 2020, offering an architecture for MVVM-based (Model-view-viewmodel based) hearing diagnosis applications. The modularity in design helped keep the app manageable, provided a means to apply its parts elsewhere, and assisted in conceptualizing data standards clinicians might grasp in workflow contexts. Testing by an otolaryngologist it demonstrated heightened efficiency in diagnostics but required considerable medical proficiency to translate its results for the deaf and hard of hearing [11]. A work in 2022 presented an audiogram digitization algorithm for insurance. It claimed adjudication with 5dB (Decibel) accuracy in scanned report threshold extraction. The open-source solution combined computer vision with JSON (JavaScript Object Notation) output generation, minimizing adjudication time via semi-automated data conversion [12]. In 2022, researchers used machine learning to identify auditory thresholds by building a binary classification model using SVM

(Support Vector Machine), in which 3 kernels were used. The audiograms and data were collected through a smartphone application, for subjects between the ages of 18 to 22 years [13]. In 2023, was confirmed a teleaudiology system which compared on-site and remote pure-tone thresholds in 50 participants. The KUDUwave audiometer with 5G connectivity revealed ≤ 3 dB differences between test conditions, proving suitability for rural use [14]. The 2023 low-cost audiometer used consumer grade materials and achieved $\pm 1\%$ intensity error [15]. 2024 witnessed an internet-based hearing check tool for Japanese health examinations. 92% concordance was evident with respect to clinical audiometry [16]. Year 2024 developments involved a decision tree based hearing loss classification mobile audiometry app. The hardware calibrated, cross platform solution featured educational content, with clinical-grade frequency range coverage [17]. In 2025 mobile phone audiometry study obtained 90% accuracy at thresholds greater than 40 dB in detecting mild loss through adaptive step size algorithms [18].

Methods and Procedures

The methodology involves the hardware assembly, software configuration and development of graphic user interface to ensure the user friendly audiometry. It includes the software and hardware integration. This prototype needs the components of Raspberry Pi 3 model B, IQaudio DAC, patient response button, 7 inch HDMI (High Definition Multimedia Interface) display, Audio

stereo plug adapter, TRRS (Tip Ring Ring Sleeve) stereo breakout extension board, headphones and an adapter for power supply. Raspberry Pi, provides enough computational power to encourage the audiometry testing. The audiologist will decide the type of audiometry to be performed, i.e., manual audiometry and auto audiometry. The patient is to wear the headphones and is given a patient response button, then the audiologist will start the audiometry process.

The IQaudio DAC ensures the quality of the audio output in the headphones by efficiently converting a digital signal into an analog signal. HDMI touchscreen provides a user friendly interface to the audiologist for selection of the audiometric testing parameters. When the patient responds positively the further testing will continue, and if they respond negatively, then the audio signal threshold gets displayed on the audiometer. The process of this audiometry process is shown in Fig.I.

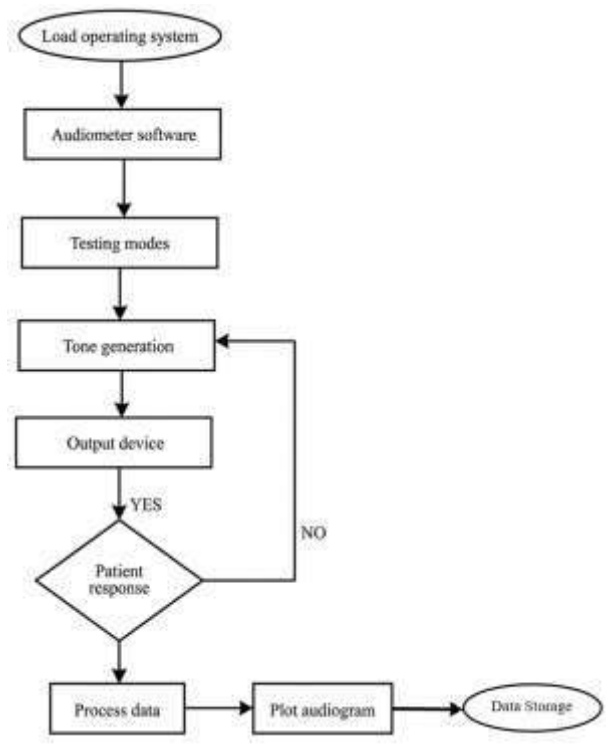


Fig. 1. Flow chart of pure tone audiometry process.

The final audiometry result in the form of an audiogram can be displayed in the pdf form as well upon generation of a report by an audiologist. The digital pure tone audiometer ensures accomplishment of the guidelines of WHO and 12 ASHA (American Speech Language Hearing Association).

A. Hardware Interface

The hardware of the system interfaces with the application, which is controlled by the caretaker. A single-board Raspberry Pi 3 Model B operates as the core processor unit that runs every program while managing both the device interface and data logging and response controls. The GPIO (General Purpose Input/Output) headers together with USB (Universal serial Bus) and HDMI

ports on this device enable users to easily connect various peripheral components. The audio output functions of the Raspberry Pi operate through its connection to an IQaudio DAC device which interfaces with the 40-pin GPIO header. The DAC device reinforces the Raspberry Pi's standard sound quality to generate minimal distortion stereo at high resolution outputs needed for diagnostic testing precision. A stereo jack at the DAC produces analog audio signals which are transmitted to patient earpieces powered by P9 Pro Max Headphones configured with the main unit. The system interaction is equipped with a 7-inch HDMI touchscreen display for operation. The HDMI connector and USB interface enable convenience so the audiologist can operate the system through its graphical user interface by connecting the display to the Raspberry Pi. Users of this interface have real-time access for adjusting test parameters and initiating sessions as well as reviewing obtained results. During testing the patient relies on the response button to show their perception of a detected tone. It is connected to Raspberry Pi GPIO pins by targeting a digital input pin and 3.3V (VCC) or GND based on pull-up or pull-down logic configuration. GPIO monitoring operates within the system program to detect button events so the system delivers precise real time response evaluation during testing procedures. A system power supply comes from a 5V/2.5A micro USB power adapter which provides power to both the Raspberry Pi and its connected peripherals simultaneously. The system's block diagram is displayed in Fig. 2.

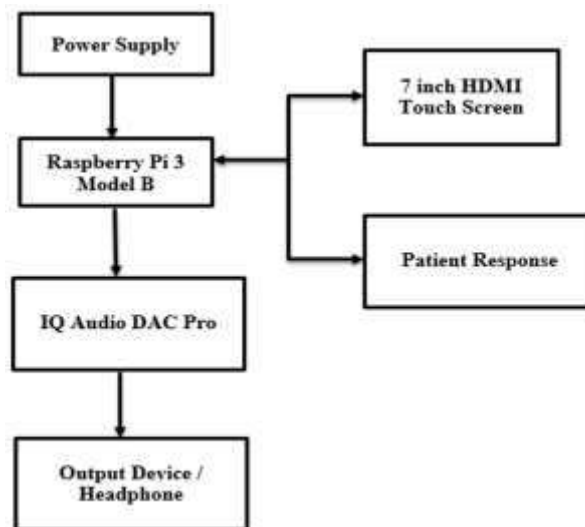


Fig. 2. Block diagram of the system.

B. Software Interface

Software development in making of this audiometry system is based on object-oriented and modular programming techniques using the Python programming language and related libraries. Source code was divided into many '.py' modules to enable separation of concerns, e.g., one module controlled the main interface (`audiometer_app.py`), another the patient data input (`patient_data.py`), and one for tone generation (`sound_module.py`). Helper files like storage of audio samples, font assets, background graphics, and PDF (Portable Document Format) templates were organized in an ordered directory structure for portability and ease of maintenance. The `AudiometerApp` class is responsible for event driven reaction to user actions coordinates playback of tones by frequency and volume selections and refreshes the graphical audiogram in real time. It keeps the application state

intact, with ear side switching, frequency progressions, and patient responses recorded accordingly. When a tone generation request is received, the Signal Processing Layer generates the requested signal. This is accomplished via a sine wave generator algorithm in Equation (1).

$$x = A \sin(2\pi ft) \quad (1)$$

Where f is the chosen frequency, A is the amplitude (adjusted according to the chosen dB level), and t is the time vector for tone duration (typically 1–2 seconds). Upon triggering a test tone a sine wave of the selected parameters is generated and played through the audio output channel. The tone is then played out through the system's default sound (headphones) through the use of the library. Volume is programmed to correspond to the chosen dB level, adjusted through scaling the waveform amplitude. When the test is complete, the user may generate a report consisting of the audiograms, and patient information. Fig. 3 shows the system after the integration of the hardware components and software algorithms used to make the digital pure tone audiometer.



Fig. 3. Final layout of designed system.

Results and discussion

The results and accuracy of calibration of the audiometry system were obtained through a comparison between expected and actual values for decibels (dB). The study involved measuring error margins in terms of amplitude (dB) to check the technical capability of the system. In order to ensure the accuracy of dB levels derived, sound level meter (SLM) mobile application was used. Standard pure tones (e.g., 1 kHz to at 20 to 80 dB HL) were presented and then were analyzed by SLM app. Error (dB) values are calculated for each value using (2).

$$E_{dB} = S_{exp} - S_{meas} \quad (2)$$

The experimental observations and the calculated error are summarized in Table I. The relationship is defined as follows:"

E_{dB} is the calculated error in decibels;

S_{exp} represents the expected sound pressure level;

S_{meas} denotes the measured sound pressure level recorded by the application.

TABLE I

OBSERVED VALUES AND CALCULATED ERROR IN DB

Frequency (Hz)	Expected dB	Measured dB (App)	Error (dB)
1000	20	16	+4.0
2000	30	32	-2
500	40	37	+3.0
125	65	57	+8.0
4000	70	68	+2.0

This method is reliant on the constraint of accuracy placed on consumer-decibel meter applications. Contrary to professional sound level meters complying with industry standards of calibration, mobile apps used in this experiment tend to display an error tolerance between ± 2 and ± 5 dB. These differences are the result of various smartphone microphone capacities, ambient noises, and capability limitations of mobile digital signal processing. Therefore, while the app's output is a fairly close approximation of real sound pressure levels, it cannot be depended on for clinical or regulatory-quality accuracy.

Clinical testing of the developed audiometer system was carried out to validate its performance characteristics in medical settings under careful supervision. Testing the device appealed to both patients and volunteers under guidance to compare its functionality versus standard clinical audiometers. From February

17th, 2025 to April 2nd, 2025, audiometric records were collected from 49 subjects using this system. Of these patients, 38.8% were male and 61.2% were female. The average age was 23.6 years. The mean hearing level (in decibels, dB) is reported for frequencies of 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. The mean hearing level for all patients was 28.98 dB (± 24.1) in the right ear and 24.69 dB (± 24.1) in the left. Using this audiometry device, the raw data can be retrieved and used with statistics software. For example, the distribution of the mean hearing levels at different age groups can be calculated in a short time typical of hearing decline can be observed with increasing age or another trait. Measurement results enable both validation of the device performance while directing to enhance functionality.

The bar chart in Fig.4 compares hearing loss severity between right and left ears across 49 individuals. Statistical analysis reveals that 71.4% of right ears (35 patients) exhibit mild hearing loss (21-40 dB), while left ears show a higher proportion of slight loss (30.6%, 15 patients). The right ear's higher severity suggests potential asymmetric noise exposure or physiological dominance, as observed in occupational hearing damage. Only 1 patient (2%) reached moderately severe loss in the right ear, indicating most cases are mild.

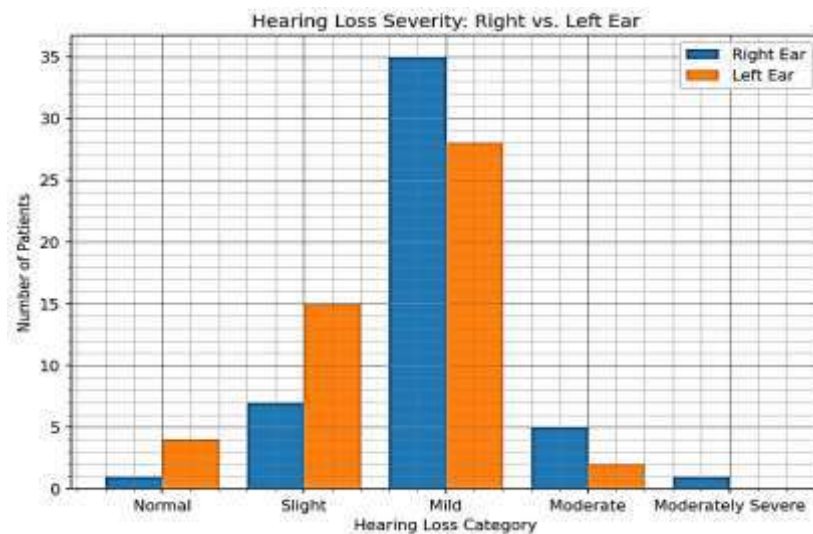


Fig. 4. Right ears show higher rates of mild impairment (71.4%) compared to left ears (57.1%)

The audiometric results shown a chart in Fig. 5 stratifies hearing loss by gender, revealing 61.2% of patients are women (30/49), but men dominate moderate cases (e.g., 4/5 moderate right-ear cases). Women cluster in slight/mild categories (e.g., 12/15 slight left-ear cases), possibly due to lower noise exposure or hormonal protective effects. Men's higher moderate rates (e.g., 60 dB right ear) align with studies linking male occupations to noise-induced loss. The subjects under 20 exhibit normal/slight loss (e.g., 11/23 cases), while 40+ group has 5/12 in moderate+. The 30–40 bracket marks the transition, with 4/16 patients showing moderate+ loss, suggesting presbycusis onset.

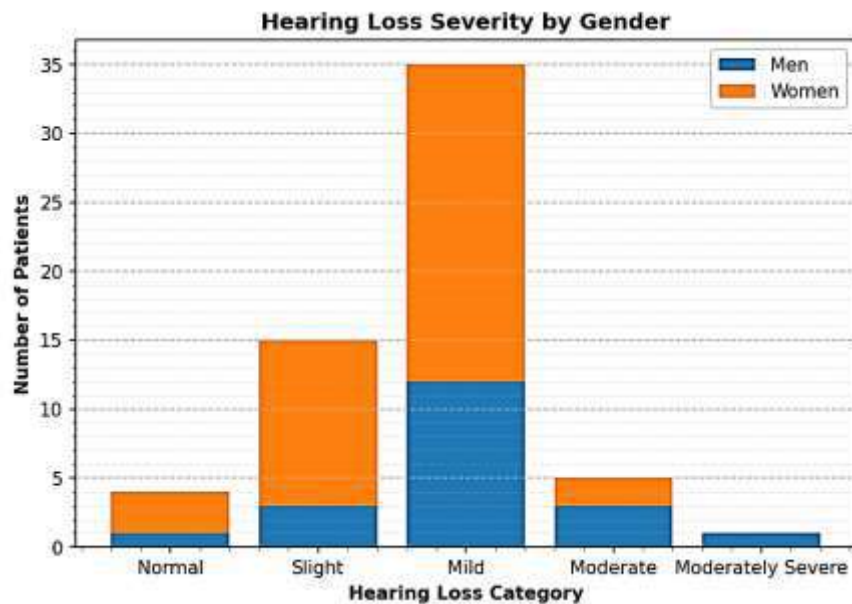


Fig. 5. Women comprise 61.2% of cases but dominate milder categories (80% of slight losses)

The audiograms of developed system and a clinical device were compared, by subjecting an individual to audiometry from both devices. Mentioned in Fig. 6 and Fig. 7 is the comparison between audiograms of this developed device and that of a clinical audiometer, namely Amplivox (Model 270).

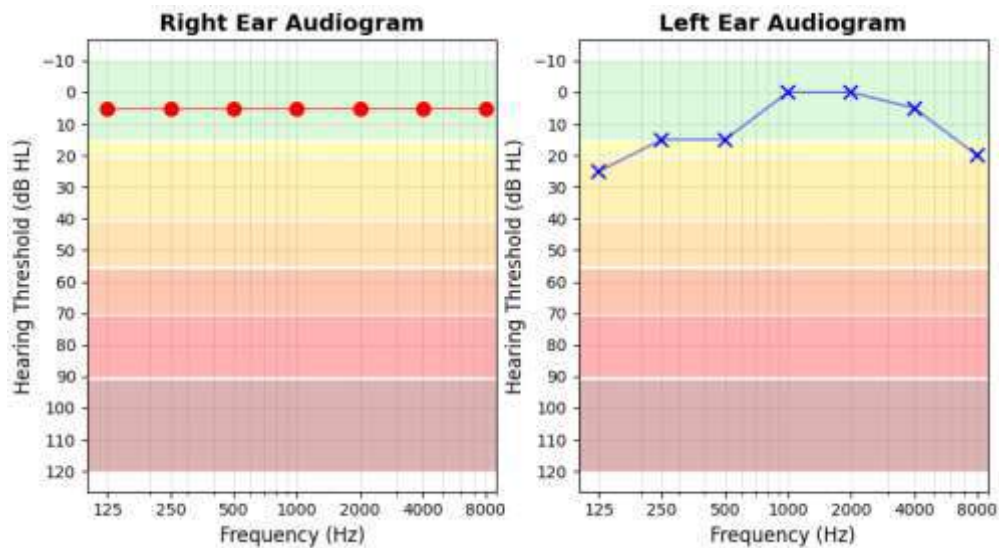


Fig. 7. Audiogram obtained via the developed system shows thresholds for the same subject, demonstrating diagnostic grade accuracy by showing strong agreement ($<5\text{dB}$ difference) with clinical audiometer

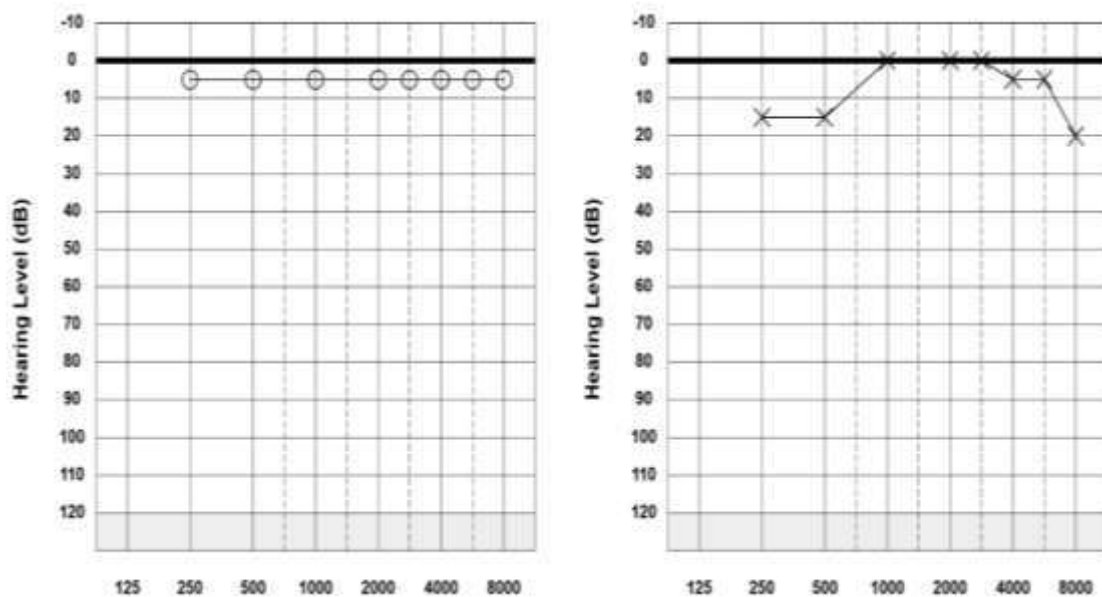


Fig. 6. Pure-tone audiogram from clinical audiometer (Amplivox 270) showing thresholds at standard frequencies. Circles for right ear (left plot) and crosses for left ear (right plot) indicate air conduction.

This direct subject specific validation demonstrates the functional accuracy of the developed system relative to standard clinical results this analysis confirms consistency and reliability. The device also underwent clinical evaluation by a licensed practitioner to validate its performance in preliminary hearing assessments. The evaluation confirmed that the device operates satisfactorily for air conduction testing in controlled clinical environments, meeting standards of accuracy, safety and usability within its intended scope.

The analysis of the audiometry system uncovered various aspects especially experimental results that varied from predicted values. The dB level accuracy variations were noted during calibration testing, when the system's output was compared to reference measurements, with most discrepancies arising within a ± 3 dB range for the majority of frequencies. These variations were most significant at far ends of the frequency range (125 Hz and 8 kHz). Relative error percentages determined over test frequencies averaged 2.8%, marginally above the desired threshold of 2%, indicated potential for enhancement in signal generation accuracy. Frequency accuracy held steady at $\pm 1.2\%$ of intended values, although intermittent anomalies cropped up in simultaneous multifrequency testing, presumably from allocation of processing resources within the audio generation subsystem. Some test cases exhibited significant departures from predicted results that are worthy of special consideration. On 12% of auto mode threshold detection, the algorithm detected thresholds 5-10

dB greater than those in manual mode for identical subjects, especially at 4 kHz frequencies. This difference seemed associated with the system's conservative method of incrementing amplitude when there was no response, tending to overestimate the actual threshold of the digital pure tone audiometer.

Conclusion

The designed audiometry system is effective to get hearing threshold and through its dual modes it achieves automatic frequency progression through its system design to provide efficient testing and maintain uniform test results while shortening the evaluation duration. The combination of automatic data presentation with resulting outputs displayed as graphs allows the patient and clinician to quickly understand evaluation data better.

This audiometer supports better treatment standards during hearing tests by getting rid of the problems and variations of traditional analog instruments. Provides real-time graphical representations of air conduction test results which increases clinical information sharing during diagnosis. This visual feedback pre-sent in the audiometer enables instant communication between clinician and patient about their hearing abilities. Clear and easy to read result presentation helps clinical practitioners make better decisions in their work.

The designed audiometer brings both affordable operation and comprehensive functionality to offer better access for healthcare providers and their patient populations during advanced hearing tests.

Future work

There are some ideas to make it more useful. By expanding its functionality through additional testing features that include speech audiometry and extended frequency range testing. These inclusion tests will give professionals the ability to examine various aspects of a patient's hearing abilities for comprehensive diagnosis. The application and integration of AI (Artificial Intelligence) features shall enable predictions of hearing loss advancement through evaluation data and medical indicators for delivering enhanced targeted patient care. Teleaudiometry can also prove to be convenient. Through the deployment of mobile application, individuals will gain the ability to schedule tests, track their progress, view their results in graphical form, store historical data for future reference and connect with experts from a distance.

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