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PASSIVE NOISE REDUCTION HEADPHONE FOR AN INTERACTIVE AND AUTOMATED HEARING SCREENING DEVICE (*i*-AHEAD)

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Abstract

Portable hearing screening systems have a positive significant impact on people's health, especially those who live in remote areas or in developing countries. In this study, *i*-AHEAD with modified TDH-49 was improved to allow a hearing screening test outside a sound-treated booth without a skilled operator. circumaural cups with an acoustic absorption material were used to enhance the passive noise reduction (PNA) in TDH-49 headphones. A microphone was attached to the headphone to monitor the surrounding noise in real-time. The improved version of the *i*-AHEAD system was calibrated and then tested in a field trial on 186 participants at test frequencies of 500, 1000, 2000 and 4000 Hz and screening cut-off levels of 40 and 25 dB hearing level (dB *HL*). The screening test using *i*-AHEAD was performed in a typical seminar room and validated with a diagnostic hearing assessment in the soundproof audiology booth. The specificity and sensitivity were 91% and 95%, respectively, at 40 dB screening cut-off point. However, the specificity decreased to 38.9% at 25 dB *HL* when the 500-Hz test tone was included. *i*-AHEAD with the modified TDH-49 headphones is useful for screening significant hearing loss at 40 dB *HL*, but further improvement is needed for this tool to be able to screen mild hearing loss at 25 dB *HL* cut-off level.

Keywords: Ambient noise, Automated hearing screening, Computer-based audiometer, Passive noise reduction.

1. Introduction

Hearing impairment is considered a serious problem that can considerably affect the health and quality of life of humans, especially in terms of employment, education and social activities. Early hearing screening is essential to overcome hearing impairment and provide a suitable treatment. The hearing impairment percentage differs amongst countries. Developed countries present less percentage of hearing loss compared with developing countries due to economic issues and lack of resources in the latter [1].

Although routine screening has been widely adopted in developed countries, children in developing countries are rarely screened for hearing loss. Many hearing screening programs, such as infant hearing screening and pure tone audiometry (PTA), are widely used to detect hearing loss. The American Speech-Language-Hearing Association suggested that children below 18 years old should undergo periodic hearing screening because hearing loss may occur at any age [2, 3].

According to Beck et al. [4] and Wu et al. [5], PTA is a hearing screening system used to investigate hearing impairment amongst children and adults. The PTA screening test has three compulsory test frequencies, namely, 1000, 2000 and 4000 Hz, and the test tone of 500 Hz is optional [6]. The test tones are generated by the audiometer and presented through standard headphones, such as TDH-49, at a specified screening cut-off level. A computer-based audiometer can be a good solution to reduce the cost and increase the PTA system portability.

In 2003, a computer-based PTA has been designed and can generate three test tones, namely, 1000, 2000 and 4000 Hz. A hearing test supervised by a specialist can be conducted in schools by using this system. Nevertheless, the need for an expert will increase the cost of the hearing screening test [7]. In 2007, a hearing screening system has been implemented in a pocket PC. Such a system can be controlled through the internet and allow data transfer from a database in remote areas [8].

However, this system still suffers from ambient noise. A computer-based audiometer (KUDUwave 5000) has been developed and used in a clinical setting [9, 10]. Nonetheless, the KUDUwave hearing screening system is still costly. In 2013, a computer-based audiometer (CAUM) was implemented in the Window operating system and uses a standard sound card [11]. However, CAUM suffers from a calibration problem and lack of ambient noise control [11, 12]. An automated and interactive computer-based hearing screening device (*i*-AHEAD) has been developed to address the above-mentioned problems and reduce the system's cost [13].

Apart from the hearing screening system, a hearing test should be performed in a quiet place to ensure the reliability of the test results. A mobile sound-treated booth or chamber is widely used in hearing screening programs to control the ambient noise levels. Normally, ambient noise levels are measured using a sound level meter (SLM) device during the test. Table 1 shows the maximum permissible ambient noise levels (MPANLs) according to American National Standard Insatiate (ANSI S3.6-2004) [13]. Nevertheless, sound-treated booths are still bulky and heavyweight and exhibit high-construction cost [14].

Table 1. Maximum permissible ambient noise levels (MPANLs).

Frequency (Hz)	MPANL (dB *SPL*)		
	0 dB hearing level (*HL*)	25 (dB *HL*)	40 (dB *HL*)
500	16	41	56
1000	21	46	61
2000	29	54	69
4000	32	57	72

Numerous studies have been conducted to overcome the drawbacks of sound-treated rooms by controlling the ambient noise and reducing the test cost. Active noise control ANC and PNR methods could be used to overcome the ambient noise problem. These methods allow hearing screening to be conducted outside an audiology clinic. The test tone of 500 Hz is often excluded from the hearing when conducting pure tone audiometry because it is susceptible to the noise. ANC headphones are regarded as one of the solutions to this problem. Commercial ANC headphones exhibit good performance to attenuate low-frequency noise by using the ANC system. In 2013, Sennheiser PXC450 circumaural ANC headphones were used to run PTA in a normal classroom [15]. The results were compared with TDH-39 supra-aural standard audiology earphones. The referral rates at the test tone of 500 Hz were decreased by using the ANC headphones. In 2013, the Bose Quiet comfort 15 ANC headphone was used for hearing screening [5]. The ANC headphones were used to present test tones at frequencies of 1, 2 and 4 kHz at the hearing levels (*HL*s) of 20 and 30 dB. However, commercial ANC headphones belong to different types and specifications, and no standard calibration procedures exist. Thus, headphones must be biologically calibrated to obtain the threshold values required for calibration.

PNR is another approach for attenuating the ambient noise level. PNR is widely used in buildings, acoustic barrier sound-proof rooms and chambers [16, 17]. It depends on the absorption and reflection of the material's specification. Although PNR is effective in mitigating high-frequency noise, it is bulky and costly when applied to attenuate low-frequency noise [18-22]. The absorption amount depends on the sound absorption coefficient (α), which is computed using Equation (1). The coefficient has a value between zero and unity. A high value indicates high absorption, whereas a low value suggests low absorption.

$$\alpha = \frac{\text{Sound Intensity Absorped}}{\text{Sound Intensity Incident}} \tag{1}$$

PNR has advantages, such as the absence of power consumption. Several acoustic materials are also safe to use, especially in human skin application. Hence, many studies focus on the improvement of PNR's limitation with low-frequency noise attenuation. A porous fibrous material made in Taiwan was used as an acoustic absorption material. The absorption coefficients of this material were measured using different thicknesses. Wang and Torng [23] proposed a directly proportional relationship exists between the sound absorption coefficients and the material thicknesses to increase the low-frequency noise attenuation.

Nevertheless, the increase in thickness results in increased weight. Natural fibre has low cost, is lightweight and considered an environmentally friendly product. Several studies investigated whether this fibre can be used as an acoustic absorption material instead of glass fibre and mineral-based synthetic materials [24]. Furthermore, this type of material presents no side effects on the human body, thereby indicating that it is safe [25]. A low-cost material with lightweight absorption is essential to attenuate noise. A composite of natural fibre-reinforced polymeric materials with urea-formaldehyde and polypropylene presents good performance against noise. The new composite is a low cost, lightweight and environmentally friendly. Jayamani and Hamdan [26] mentioned that the absorption coefficient of this material is high at high frequency but poor at less than 0.025 in low frequency, e.g., below 1000 Hz.

A commercial device known as KUDWave hearing screening system can perform a hearing screening test in remote areas, such as in a normal classroom, without them needing a sound-treated room. The software is combined with circumaural ear cups and powered by a USB cable. The headphones can attenuate the noise level by using PNR and perform air and bone conduction. Moreover, the headphones consist of an inserted earphone surrounded with the circumaural cup to increase the attenuation levels [14]. Each ear cup is connected to a microphone to monitor the ambient noise in real-time. The main drawback is that a technician is needed to carefully insert the ER3A earphones into the ear canal during a hearing screening test. This work described the enhancement of the *i*-AHEAD system by using the acoustic absorption material to improve the PNR method for the TDH-49 headphone. The developed headphone was calibrated according to the standards, and a pilot study has been conducted to determine the specificity and sensitivity of the system.

2. Materials and Methods

The *i*-AHEAD system consists of hardware and software, which are used to run the automated hearing screening in accordance with the standard, with the user-friendly graphical user interface. The hardware consists of a laptop, a microphone, an external sound card and modified TDH-49 earphones [13]. The Dell I3 touchscreen laptop was used as an audiometer. The touch screen and mouse can be used by the user to respond to the test tone. A customised hearing screening software used in the *i*-AHEAD system can be installed on any PC with low specification: Operating system (Windows), Processor (Intel or ADM × 86), H.D (2 GB free space), Memory (2 GB).

The external sound card is used to increase the resolution setting, minimise the quantisation error for headphones and microphone and make the calibration values for microphone and headphone unrelated to the PC’s internal sound card.

2.1. Acoustic absorption materials

Two-layer acoustic absorption material known as AcoustiPack, which is produced by Acoustiproducts, is used in this study. The AcoustiPack material is lightweight, flexible, affordable, and exhibits good noise reduction because of a high absorption coefficient value. The material’s thickness is approximately 4 mm. AcoustiPack construction is shown in Fig. 1, and additional information can be found in a previous study [27]. Acoustic foam and barrier are effective in attenuating high-frequency and low-frequency noises, respectively. Therefore, AcoustiPack is suitable for reducing high and low-frequency noises.

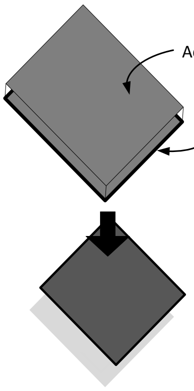


Fig. 1. Two-layer materials.

2.2. Development of PNR headphones

The TDH-49 headphones were modified by using 3M circumaural ear cups and AcoustiPack materials. The ear cups were covered with the AcoustiPack materials from the outside to attenuate the surrounding noise. They were stuffed with a sponge from the inside to tightly place the TDH-49 speaker inside the cup. Based on studies by Shalool et al. [28], the headphone modification, which has a 3.5 jack audio cable connected to the headphone and a microphone attached to the headband to monitor the ambient noise in real-time, is shown in Fig. 2.

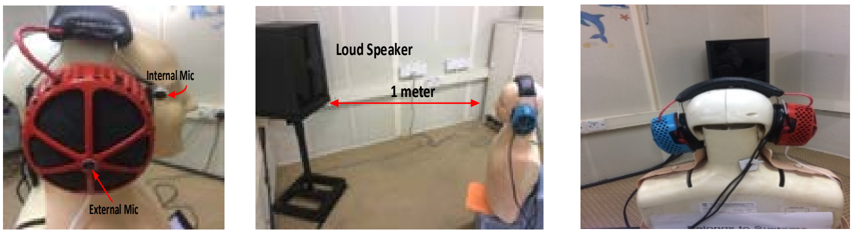
(a) Modified circumaural Tdh-49.

(b) Tdh-49 supra-aural.

Fig. 2. Modified TDH-49 headphone.

2.3. Evaluation of headphone's PNR

PNR assessment is necessary to evaluate the performance of the modified TDH-49 headphone against noise. The measurement was conducted in an anechoic room. White wideband noise (10 Hz to 8000 Hz) was used as an excitation noise. The headphones were carefully placed on the manikin. The SLM software with two channels developed in Matlab was used. Each channel used a microphone. The internal microphone was properly fixed inside the cup, and the external one was fixed outside the cup as shown in Fig. 3. The distance (d) between the manikin and speaker was 1 m at θ equal 0° angle position. The speaker started playing white noise, and the software started to simultaneously take the reading from both microphones and record the noise level at one-third octave bands.



(a) External and internal microphones. **(b) Manikin wearing headphones with 0 angle.** **(c) Manikin facing the speaker.**

Fig. 3. PNR measurements in an anechoic room.

2.4. Headphones and microphone calibration

Table 2 shows the relationship between the sound pressure level (SPL) and the *HL* for the TDH-49 headphones in accordance with the standard values. The measured sound levels in Table 2 should be within ± 3 dB at any test frequencies between 500 and 3000 Hz and ±4 dB at 4000 Hz [13]. These earphones are commonly calibrated with a NBS-9A 6-cc coupler (Bruel and Kjar Sound and Vibration Measurement A/S, Narum, Denmark) [29, 30]. In the current study, measurements were performed to determine a set of values that can be used to transform *SPL*s, with reference to an NBS-9A coupler and to *HL*s. This measurement was conducted inside a chamber. Figure 4 illustrates the headphone calibration procedure. First, the SLM microphone must be calibrated [31]. Thereafter, TDH-49 cup was mounted on the 6cc-9A coupler without any gap. Approximately 500 g weight, which is equivalent to the force of the headband, was placed on the cup. One-third octave band was selected on the SLM and the same frequency was adjusted on the software. The reading was taken when the tone was sent. The reading was amplitude in voltage, which will be used by the hearing software to generate the test tone signal at a precise *HL* in each frequency. Equation (2) was used to calculate the *HL* in dB, whereas, Eq. (3) was used to calculate the *HL*s below 40 dB, because they are difficult to measure by SLM [13, 27], as follows:

$$HL\ (\text{dB}) = 20\ log_{10}\ \frac{a_i}{a_{i+1}} \tag{2}$$

where i = 0,1,2,3,.......a_i is the amplitude corresponding to the measured *HL* in (dB).

$$a_{i+1} = a_i \times 10^{(-5/20)} \tag{3}$$

Microphones, which are used with the modified TDH-49 headphones, were first calibrated to obtain an accurate ambient noise level. The calibration process was carried out using a program based on MatLab with a QC10 class 1 acoustic calibrator. The program based on SLM (94 dB *SPL*) was used to adjust the microphone calibration parameter, such as the volume. An omnidirectional microphone has dimensions of 9.7 mm × 4.5 mm. A sensitivity of 40 ± 3 dB is attached to the headband and is used to measure the ambient noise in real-time. The microphone was small. Thus, a gap was observed when it was inserted into the calibrator cavity. Hence, the microphone was inserted inside a holder to achieve a good fit in the calibrator cavity and to eliminate the gap. Subsequently, the calibration process was initiated, and the calibration parameter was measured and saved in the SLM software.

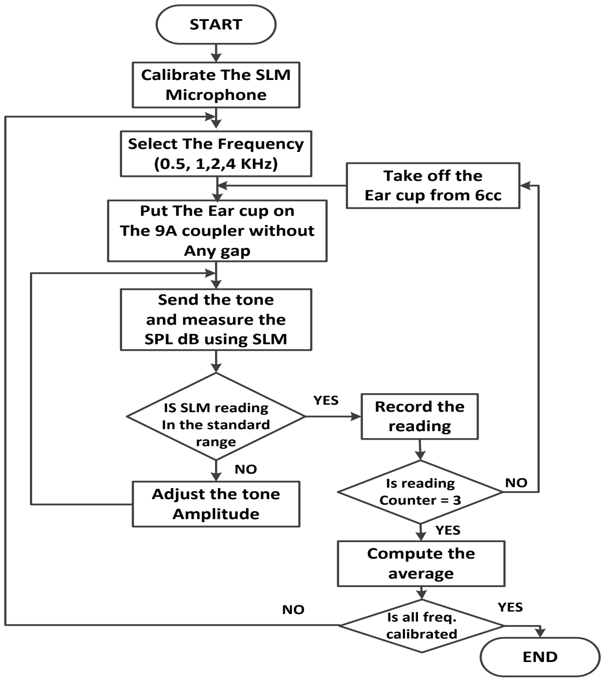


Fig. 4. Headphone calibration procedure.

Table 2. Reference threshold levels for TDH-49 headphones.

Frequency (Hz)	Referred threshold for TDH-49 earphone, dB	SLM reading, dB
500	13.5	83.5
1000	7.5	77.5
2000	11	81.0
4000	10.5	80.5

3. *i*-AHEAD Software

The *i*-AHEAD software was implemented using MatLab under Windows platform [13]. The software consisted of four parts. The first part was the SQL database, which was used to save the headphone and microphone calibration values, user biodata, hearing screening result and school or hearing screening centre address. The system used an internal host to temporarily save the data on database tables if an Internet connection is unavailable. The data was transferred to the external server when an Internet connection was available. The second part was the help, which was used to provide complete test guidelines, such as the proper way of wearing the headphones and distinguishing between right and left headphone cups. The third part was an automated four-frequency pure-tone hearing screening procedure as shown in Fig. 5. The 500 Hz test tone can be included or excluded. The fourth part was a real-time noise monitoring software created in Matlab. Table 3 shows the hearing screening test classification for a test tone at the same frequency. However, when the result was noisy, the system paused the test until the noise levels dropped below the MPANLs according to Table 1 or when the user exits the test without saving the test result.

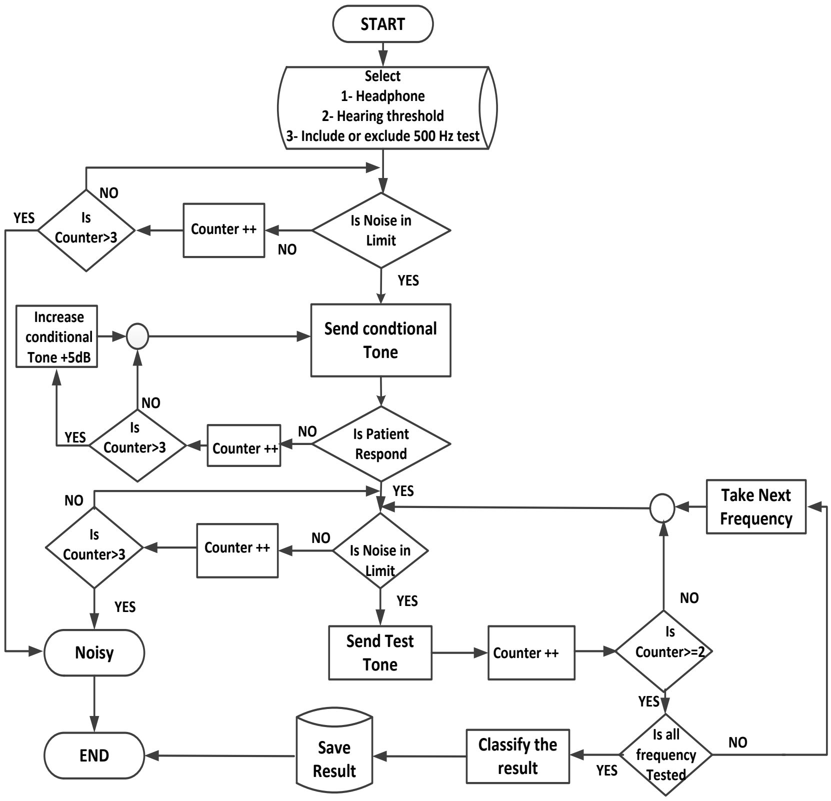


Fig. 5. Hearing screening procedure.

Table 3. Test results classification under different conditions.

Test tone 1	Test tone 2	Test tone 3	Result
Response	Response	No test tone	Pass
No response	Response	Response	Pass
Noisy	Response	Response	Pass
Response	No response	No response	Referral
No response	Response	No response	Referral
No response	No response	No test tone	Referral
Noisy	Response	No response	Referral
Noisy	Noisy	No test tone	Noisy
Response	Noisy	Noisy	Noisy
No response	Noisy	Noisy	Noisy

Field trial using *i*-AHEAD

The study was carried out in two stages, as follows: hearing screening using *i*-AHEAD system inside a seminar room, which represents a typical classroom; and a diagnostic hearing assessment in a soundproof audiology booth for validation. The diagnostic PTA hearing assessment served as the gold standard test to allow the computation of *i*-AHEAD's sensitivity and specificity. The limitation of this study was constrained by using air-conduction PTA hearing screening at four frequencies (500, 1000, 2000 and 4000 Hz) at intensity levels 25 and 40 dB *HL*.

The tests were conducted by two final year interns in audiology under the supervision of a qualified audiologist. A total of 186 participants were recruited at the Audiology and Speech Sciences Clinic Universiti Kebangsaan Malaysia (UKM). Table 4 presents the demographic characteristics of the participants classified by gender and age. The participants obtained sufficient explanation before the test, and *i*-AHEAD software also provided further information at the beginning of the test. The children's parents obtained a complete explanation about the test procedure and signed a written consent letter. The study protocol was approved by the UKM Research Ethics Committee for the Prototype Research Grant Scheme code PRGS/1/12/TK02/UKM/02/1.

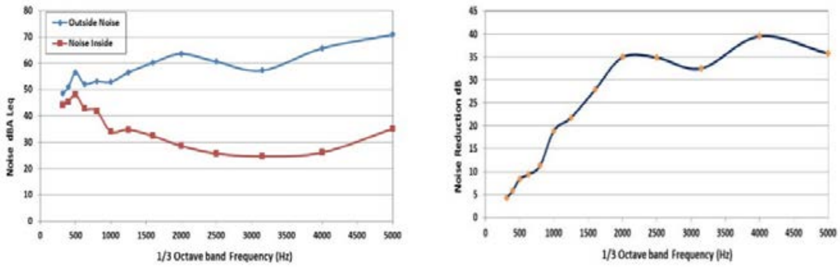
Table 4. Age and gender distribution of the participants.

Age (Years)	Female (*n* = 13)	%	Male (*n* = 73)	%	Total (*n* = 186)	%
5-12	23	20.35	27	37	50	26.88
13-18	20	17.7	11	15	31	16.67
19-30	39	34.5	26	35.6	65	35
31-55	27	23.9	7	9.6	34	18.28
> 55	4	3.54	2	2.7	6	3.2

4. Result and Discussion

4.1. Passive noise reduction

Figure 6 shows the noise inside and outside the cup and the PNR for the cup. A considerable noise reduction, especially at more than 1 kHz, was obtained. The noise reduction rates at 500 Hz were 15.6 and 16.63 dB for the right and left ear cups, respectively. Correspondingly, the reduction rates were 24.94 and 24.1, 33.4 and 31.7, and 34.49 and 33.1 dB at 1000, 2000 and 4000 Hz, respectively. No large difference in PNC was observed between the right and the left ear cups.



The noise outside and inside the ear cups. **The noise attenuation by the headphone.**

Fig. 6. Headphones passive noise reduction.

4.2. Headphone calibration

Figure 7 presents a linear relationship between the calibration values and the hearing level threshold for the right and left headphones. The right and left cups graphs were very close to each other in four frequencies. However, the graphs were different, because the position of the cup on the 6-cc coupler changes during the calibration process. The X-axis represents the calibration values in volt, whilst the Y-axis indicates the hearing level (dB). Table 5 shows the calibration values in (volt) at 25 and 40 dB *HL* cut-off that were inserted to the database table known as headphone calibration. Thereafter, the hearing screening software retrieved the values depending on the cut-off threshold for each frequency.

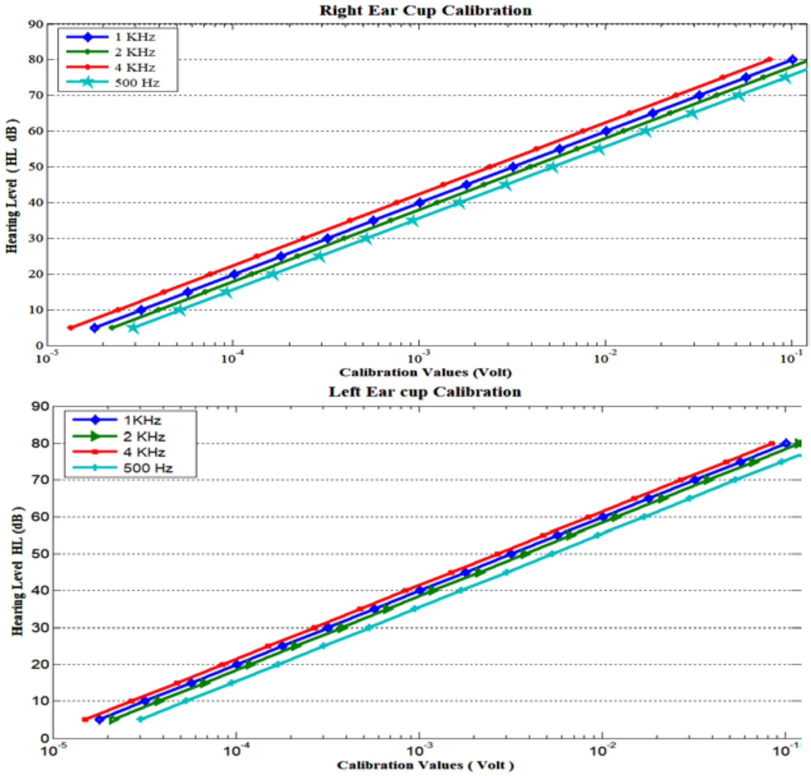


Fig. 7. Calibration values (volt) vs. hearing levels (dB *HL*) relationship.

Table 5. Calibration values in (volt) of the modified headphones.

dB *HL*	Ear	condition	1 kHz	2 kHz	4 kHz	500 Hz
25	Left	0.0031	1.743 *e*-4	2.38 *e*-4	9.95 *e*-5	2.99 *e*-4
	Right	0.0029	1.631 *e*-4	2.32 *e*-4	1.13 *e*-4	2.97 *e*-4
40	Left	0.0031	0.0009803	0.00135	0.00056	0.0017
	Right	0.0029	0.0009171	0.0013	0.00064	0.0017

4.3. Ambient noise level monitoring

The noise levels inside the seminar room were measured during the hearing screening test in real-time by using the microphone attached to the headphone headband and by using the SLM instrument. The noise levels were measured in one-third octave band frequency. The noise reading was then recorded by the software in a text file. The participant's name, time and date were saved in the text file. The noise was separately recorded for each frequency during the test time, and the software compared the real-time noise levels at each test frequency with the

MPANLs in Table 1. Subsequently, the comparison results were used by the software to determine whether the test should be continued or paused. Figure 8 shows that the optimal reading was an *SPL* of 60 dB at 500 Hz. The minimum value was an *SPL* of 46 dB at 4 kHz. The maximum noise levels at 1000 and 2000 Hz were 48.89 and 48.2 dB *SPL*, respectively (Fig. 8). The noise level may not be sufficient to run the test at a screening cut-off point of 25 dB. However, these readings fluctuated. Thus, the system sent another tone when the noise at the present tone dropped below the MPANLs. Table 6 shows the number of reading in which, the noise exceeded the standard levels at each test frequency during the test time. Evidently, the maximum number was 18 times at 500 Hz, because the ambient noise was at low frequencies. Therefore, the 500 Hz test tone may be masked by the ambient noise, especially at a cut-off threshold 25 dB *HL*.

Table 6. Number of times that noise exceeds the MPANLs.

Frequency (Hz)	500	1000	2000	4000
MPANLs at 25 dB *HL*	41	46	54	57
Number of times noise exceeds MPANLs	18	6	0	0

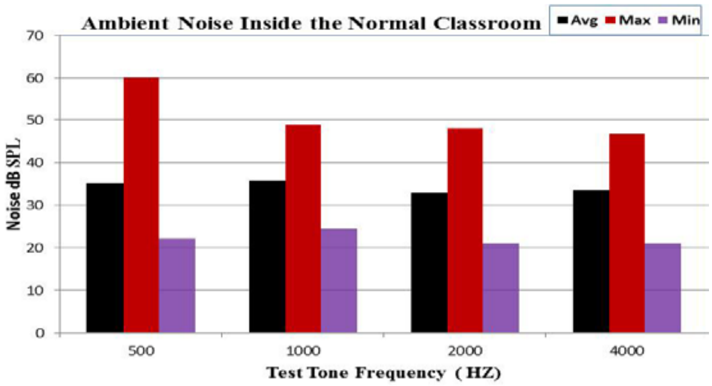


Fig. 8. Real-time ambient noise reading.

4.4. Field trial using *i-AHEAD*

Pure tone audiometry is still the most widely performed test worldwide. This measurement has been the primary standard for a long time because of its high specificity and sensitivity. Sensitivity and specificity are important for any hearing screening test. The results of the *i*-AHEAD system and primary standard clinical portable audiometer were calculated using a confusion matrix. Figure 9(a) shows the sensitivity and specificity at the screening level of 25 dB *HL*. Such factors were computed with and without the test tone of 500 Hz to show the effects of ambient noise on the low-frequency test tone. The *i*-AHEAD exhibited a sensitivity of 92.3%, which slightly decreased to 88.2% when the test tone of 500 Hz was included. The specificity was 38.9%, and this improved to 79.6% when the test tone of 500 Hz was excluded. The *i*-AHEAD still suffered from low-frequency ambient noise, because the system measured the noise outside the earcup cavity. The sensitivity and specificity at the screening cut-off level of 40 dB *HL* were 95% and 92%, respectively as shown in Fig. 9(b).

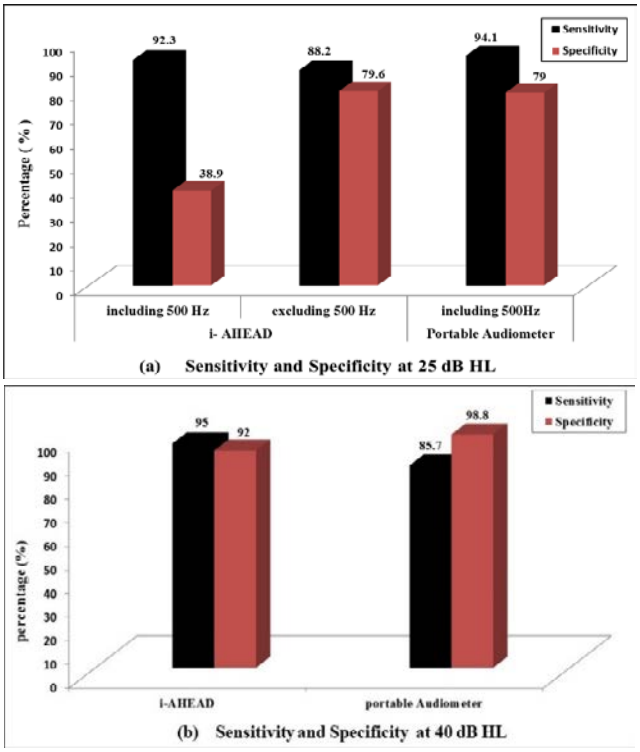


Fig. 9. Sensitivity and specificity of *i*-AHEAD and the portable audiometer.

5. Conclusion

The *i*-AHEAD uses the modified TDH-49 headphones to overcome the influence of the ambient noise and reduce the cost due to the use of the anechoic booth. Portability is another added feature of the system. The auto-run feature increases the integrity between the test and the patient in the absence of an expert. The sensitivity and specificity were measured using data collected at a normal classroom. At 40 dB *HL*, the screening cut-off level showed relatively high sensitivity and specificity without the inclusion of the 500 Hz test tone. However, at a low-level screening cut-off point (25 dB *HL*), the specificity of the *i*-AHEAD system did not reach 80%, even though the 500-Hz test tone was excluded. This finding suggested that further improvement is needed to enhance the sensitivity and specificity of this system at this low screening cut-off threshold. The hearing screening results showed that the *i*-AHEAD with the modified TDH-49 headphone is a promising screening tool to be used in a typical, fairly quiet room outside the audiology booth. My-SQL can be used to create a database with the local host to increase data storage and security levels. Future work will focus on *i*-AHEAD implementation on mobile platforms, such as iOS or Android, to increase the system's portability. The headphone design will be improved for manufacturing capability. Collaboration with local manufacturers is also necessary to reduce the commercialisation gap. Several standard operating procedure and design must be effectively documented and comply with the ISO9000 and ISO13485. This compliance will ease the product certification process in the near future.

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Nomenclatures

a_i	Amplitude of the current hearing level, Volt
a_{i+1}	Amplitude of the next hearing level, Volt
d	Distance between the loudspeaker and the Manikin, meter
HL	Hearing level, dB
n	Number of participants
SPL	Sound pressure level, dB

Greek Symbols

α	Absorption coefficient, ratio
θ	angle between the head and the Manikin, degree

Abbreviations

PC	Personal Computer
ANC	Active Noise Cancellation
ANSI	American National Standard Insatiate
ASHA	American Speech-Language-Hearing-Association
CAUM	Computer-based Audiometer
GUI	Graphical User Interface
ICT	Information and Communication Technology
ISO	International Organization for standardization
i-AHEAD	Interactive and Automated Hearing Screening Device
MPANLs	Maximum Permissible Ambient Noise Levels
PC	Personal Computer
PNR	Passive Noise Reduction
PTA	Pure Tone Audiometry
SLM	Sound Level Meter
SQL	Structured Query Language
UKM	Universiti Kebangsaan Malaysia (National University of Malaysia).
WHO	World Health Organization

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