CoDAS
ISSN 2317-1782 (Online version)

Original Article
Artigo Original

Accuracy of affordable instruments for hearing screening in adults and the elderly

Acurácia de instrumentos de custo acessível para triagem auditiva de adultos e idosos

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Keywords

Hearing
Hearing Loss
Hearing Tests
Audiology
Adults
Health Policy
Presbycusis
Health of the Elderly

Descritores

Audição
Perda Auditiva
Testes Auditivos
Audiologia
Adultos
Política de Saúde
Presbiacusia
Saúde do Idoso

ABSTRACT

Purpose: To evaluate the accuracy of affordable instruments for hearing screening of adults and the elderly. **Methods**: This study was carried out with users of a Hearing Health Service of the Unified Health System. All were screened with the MoBASA smartphone application, the Telehealth audiometer (TH) and the electronic version of the Hearing Handicap Inventory for the Elderly - screening version - eHHIE-S. The examiners were blinded to the results of the screening tests and pure tone audiometry (PTA). Hearing impairment was considered for those with a PTA quadritonal mean greater than 40 dB in the best ear. Sensitivity, specificity and positive and negative predictive values (PPV and NPV, respectively) were calculated. The Kappa index was used as an agreement indicator between the PTA and the screening results. **Results**: The sample consisted of 80 individuals between 18 and 94 years old (55.18 ± 20.21). In the PTA test, 21 individuals (26.25%) had typical hearing and 59 (73.75%) hearing loss. In the hearing screening tests, sensitivity, specificity, PPV and NPV values greater than 75% were observed with the MoBASA as well as in terms of sensitivity and NPV of the TH and the eHHIE-S. The TH and the eHHIE-S specificity and PPV were less than 75%. The Kappa index indicated a substantial agreement (0.6) between the PTA and the MoBASA screening results. The TH and the eHHIE-S showed regular agreement (0.3). **Conclusion**: MoBASA proved to be an accurate method for hearing screening of adults and the elderly with disabling hearing loss.

RESUMO

Objetivo: Avaliar a acurácia de instrumentos de custo acessível para triagem auditiva de adultos e idosos. **Método:** Este estudo foi realizado com usuários de um Serviço de Saúde Auditiva do SUS. Todos foram submetidos a triagem com o aplicativo de *smartphone* MoBASA, o audiômetro Telessaúde (TS) e a versão eletrônica do Questionário de *Handicap* da Audição para Idosos (*Hearing Handicap Inventory for the Elderly – screening version* - eHHIE-S). Os examinadores foram cegos quanto aos resultados dos testes de triagem e para os dados de audiometria de tom puro (ATP). Foram considerados com deficiência auditiva aqueles com média quadritonal na ATP maiores que 40 dB na melhor orelha. Sensibilidade, especificidade e valores preditivos positivo (VPP) e negativo (VPN) foram calculados. O índice Kappa foi usado como um indicador de concordância entre ATP e os resultados da triagem. **Resultados:** A amostra constou de 80 indivíduos entre 18 a 94 anos (55,18 ± 20,21). Na ATP, 21 indivíduos (26,25%) apresentaram audição normal e 59 (73,75%) perda auditiva incapacitante. Nos testes de triagem auditiva observou-se valores de sensibilidade, especificidade, VPP e VPN maiores do que 75% no MoBASA e na sensibilidade e VPN do TS e eHHIE-S. Já a especificidade e VPP do TS e eHHIE-S foram inferiores a 75%. O índice Kappa indicou concordância substancial (0,6) entre o ATP e os resultados do MoBASA. No TS e eHHIE-S foi constatada regular concordância (0,3). **Conclusão:** O MoBASA demonstrou ser um método acurado para triagem auditiva de adultos e idosos com perda auditiva incapacitante.

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Received: April 15, 2020

Accepted: September 30, 2020

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Financial support: nothing to declare.

Conflict of interests: nothing to declare.

INTRODUCTION

It is estimated that more than 5% of the world population has disabling hearing loss, with the majority of them living in low-income countries, where access to identification, diagnosis, and intervention services for hearing loss is restricted[1]. In Brazil, a population-based study indicated that 6.8%[2] of the population were living with disabling hearing loss, requiring intervention. Hearing loss predominates in the age group above 60 years old[2]. Therefore, hearing loss prevalence is high especially in elderly individuals and its frequently insidious appearance hampers self-identification. Hearing screening can allow the identification of these individuals, enabling referral for diagnosis and intervention.

Greater awareness regarding hearing loss and its comorbidities is required as part of the annual assessment of adults and the elderly in primary care, besides encouraging the use of hearing screening instruments and referral for complete audiological assessment before any treatment[3].

In Brazil, the National Health Policy for the Elderly stated the importance of early identification and intervention and the need for surveillance by health teams through application of screening tests to detect hearing disorders, among others[4]. However, large-scale hearing screening programs for adults and the elderly are still restricted in the country due to different factors that include the costs and training of human resources to perform the procedure, the time needed for its performance, and equipment cost[5].

Hearing screening instruments must be fast, simple to administer, safe for the patient, and comply with performance criteria, that is, be sensitive and specific[3]. Different approaches can be used for hearing screening in the adult and elderly population, comprising, among others, tests with uncalibrated and calibrated stimuli and physiological procedures and questionnaires to assess self-perception of hearing difficulty or participation restriction. Regarding the self-assessment of participation restriction, the *Hearing Handicap Inventory for the Elderly Screening Version* – HHIE-S[6] was suggested for being a validated instrument with easy and fast application[7]. In addition, the application of the electronic version of HHIE-S can facilitate scoring, storage, and transmission of data.

More recently, software-based instruments for audiometric screening that can be used in portable computers[5], replacing the purchase of specialized and expensive equipment, have been studied. The Telehealth (TS) audiometer is an example, which uses conventional headsets and low-cost USB, enabling audiometric screening with results similar to the procedures performed with conventional equipment[5].

The high availability of mobile devices such as smartphones [8-14] and tablets[15,16] make them a convenient platform for software development (applications or *"apps"*) in the health area. A review study[17] showed medical applications that permeate all clinical care, contributing from health promotion to intervention. Clinical decision support applications have enormous potential to improve care access and quality[17]. Regarding hearing screening, the portability, accessibility, low cost, and possibility of self-administration of tests offer opportunities to face some challenges of the implementation of screening programs for low-and middle-income countries[18]. However, it is important that these applications undergo a thorough technical and clinical validation prior to being available to the end user.

The availability of software-based instruments also facilitates the implementation of distance audiology or teleaudiology services[19]. This is important in Brazil as although the coverage and actions regarding hearing health within the scope of the Unified Health System (SUS) have increased, regional inequalities in the distribution of hearing health care services persist[20]. Thus, it is important to evaluate low-cost instruments that facilitate the transmission and monitoring of information aimed at reducing the costs of hearing screening programs without compromising the quality of the results[5].

Therefore, the aim of this study was to evaluate the accuracy of the following three hearing screening instruments: a smartphone application for audiometric screening developed in Brazil – *Mobile-based Affordable Screening Audiometer* (MoBASA); the software-based Telehealth audiometer[5]; and the electronic version of the HHIE-S questionnaire to identify disabling hearing loss in adults and the elderly.

METHOD

Data collection was conducted after approval by the institution's research ethics committee, no. 849,004. All participants signed the Informed Consent Form (ICF).

Participants

Individuals admitted to Hearing Health Service accredited by the Unified Health System (SUS) participated in this research. Participants were voluntarily recruited by convenience sampling in the waiting room of the service aforementioned when awaiting consultation in the sectors of audiological diagnosis, electrophysiology of hearing, and PSAP (Personal Sound Amplification Products) selection/adaptation. The individuals were approached directly by the researchers, received clarifications regarding the research objectives and signed the ICF if they agreed to participate. Researchers did not have prior access to the information contained in the medical records of participants, including the reason for consultation and, when available, the results of audiological asessments.

All individuals using this service were eligible for the study except for those who did not perform pure-tone audiometry (gold standard) with the speech therapists of this service.

Hearing screening procedures

Each hearing screening procedure used in this study was performed by a different evaluator blinded to the results of the other screening procedures. All procedures were applied in a single silent room with no acoustic treatment in the following order: MoBASA application, TS audiometer, and electronic version of the HHIE-S.

The application *Mobile-based Affordable Screening Audiometer* (MoBASA) was developed for the Eclipse™ platform in Java™ for Android 4 or superior operating system installed on

a smartphone. MoBASA must be applied by a speech therapist or doctor with knowledge in the field of audiology, not being a self-administered application.

In this study, the application was installed on a Galaxy Win smartphone (Samsung) and calibrated according to the characteristics of this model, before use. This procedure was performed only once before being applied to all individuals in the study.

The MoBASA calibration method was developed to be able to use a low-cost sound level meter (ICEL Manaus decibel meter, DL-4020). The pure tones used in the MoBASA calibration were synthesized using the software Audacity® in 16 bits, being single-channeled and with sampling frequency of 44100 Hz. The referred software was installed on a HP Compaq 6005 computer. Pure tones in the frequencies of 500, 100, 2000, and 4000 Hz lasting one second and with an increase and decrease time of 3% were used as stimuli.

Calibration of stimulus intensity for each frequency was performed with the smartphone positioned at 0° azimuth and at a distance of 5 cm from the decibel meter, with this distance being also observed when the smartphone was positioned close to the participant's ear during the screening procedure. The stimuli were presented through the smartphone and the volume and gain controls of the MoBASA application were adjusted until the decibel meter indicated the desired value (e.g. 40 dB HL), with tolerance of up to 5% and discounting the noise level of the ambient where calibration was performed.

MoBASA also uses the smartphone microphone to measure ambient noise (dB A) in real time in order to identify whether the noise is excessive and potentially interfering with screening results. For calibration of the smartphone microphone, a pure tone of 1000 Hz was used with duration of three seconds and increase and decrease times of 3%. Since the equipment is stereo, two speakers were used (FF-70 SO400), being positioned one meter away from each other. The smartphone was positioned next to the decibel meter at the midpoint of the distance between the two speakers. A tone of 1000 Hz was reproduced via the software Audacity®. Tone intensity was adjusted until the decibel meter registered 90 dBA. The root mean square (RMS) calculated by MoBASA was recorded simultaneously using the smartphone microphone. This procedure was repeated with stimulus intensity being decreased by approximately 10 dBA each time until reaching the noise level in the calibration room, that is, in the absence of stimulus. The $f(x) = A*\ln(x)+B$ logarithmic regression model was performed with the RMS values recorded in order to obtain the calibration curve of the smartphone microphone. The respective calibration parameters (volume, gain, and A and B) were stored in the memory of MoBASA for use during screening of all individuals.

After conduction of the calibration process aforementioned, the participants' identification data (name, age, and sex) were inserted into the MoBASA initial screen. The evaluator subsequently selected the side to be screened (right or left ear). The smartphone was positioned 5 cm away from each participant's ear. Pure tones in the frequencies of 500, 1000, 2000, and 4000 Hz were presented using the smartphone speaker at an intensity of 40 dB HL. This was possible since both dBA and dB HL are referred to dB SPL (sound pressure level) through a set of coefficients normalized for each frequency value. Thus, by knowing the frequency presented to the decibel meter (which occurs in the calibration of pure tones), it is possible to transform dBA into dB HL by applying the parameters -0.3, -0.5, +0.3, and +4 for frequencies of 500, 1000, 2000, and 4000 Hz, respectively. Under these conditions, the use of a decibel meter calibrated by dBA allows obtaining MoBASA calibration results in dB HL for stimulation and in dBA for determination of ambient noise level.

Participants were instructed to raise their hands when hearing the stimulus. The order of frequency of the MoBASA test and the side on which the test started were randomized. A "pass" result was considered when the individual responded to the stimuli presented and a "fail" result was considered when the individual did not respond to at least one stimulus presented in at least one of the ears tested, being the criterion of the MoBASA application. Thus, a stimulus at the intensity of 40 dB HL was presented by frequency. The pass/fail criterion was determined based on the WHO determination of disabling hearing loss, as this type of loss is the focus of the SUS hearing health care.

The registration data of the professional, the clinic, and the patient, calibration parameters, and screening results were stored in a SQLite database into the smartphone SD card. These data were synchronized to the Computer-based Affordable Screening Audiometer (CoBASA), a computer software (Windows®, MAC® or Linux) that allows the import of MoBASA data from one or more smartphones, allowing to generate a database of the screenings performed.

Subsequently, the individuals were submitted to assessment using the software TS audiometer and following specifications in the literature[5]. The software TS was installed on an Acer Aspire One netbook (10.1" screen, Intel Atom Inside processor) for its portability, with Windows XP as operating system, which is a prerequisite for its installation. The TS uses a LifeChat LX-3000 (Microsoft®) headset with its own USB sound card, supra-aural headphones, and a built-in microphone. This microphone analyzes ambient noise intensity and the software informs the evaluator if it is very strong and hampering results. The parameters of headset calibration are saved in the software. The TS provides pure tones in the frequencies from 250 to 8000 Hz, with minimum intensity of 10 dB and maximum intensity of 70 dB HL[5].

During screening with the software TS, the participant was positioned backwards to the netbook in order to not have visual access to the evaluator or the computer. The frequencies of 500, 1000, 2000, and 4000 Hz were tested in both ears, following the same order for all individuals assessed. The participants were instructed to raise their hand whenever they heard a sound stimulus. The ascendant-descendant procedure was used to identify the minimum response level (the individual could detect at least 50% of the stimuli presented). The analysis was based on responses to the presentation level at 40 dB HL. The presence of minimum response levels greater than or equal to 40 dB HL in at least one frequency and in at least one ear was considered "fail". The results were stored in the software database and recorded in a specific protocol by the researchers.

The Hearing Handicap Inventory for the Elderly Screening Version (HHIE-S) is a simplified version containing 10 of the 25 questions of the *Hearing Handicap Inventory for the Elderly - HHIE-S*[21], which is a questionnaire developed for handicap assessment for the elderly. However, it was applied in this study also for adults, since the simplified questions are pertinent to both adults and the elderly.

The HHIE-S adapted for Brazilian Portuguese was made available electronically via the internet only for the researchers and for the purposes of data collection in the present study. Five items of the HHIE-S refer to the social/situational scale and five refer to the emotional scale. For each question, the following three answer options are available: "yes" (4 points), "sometimes" (2 points) and "no" (0 points). Participants were instructed to read the items and choose the answer most similar to their judgment. At the end of each application, a report was generated with the total score obtained by the individual. This total score, given by the sum of the points obtained in each item, could range from 0 to 40 corresponding to the range of perception of the auditory handicap, as follows: 0-8 points (no hearing handicap); 10-23 points (mild to moderate handicap); and 24-40 points (significant handicap). In the present study, scores below 8 points or greater than 10 points were considered as "pass" and "fail", being analyzed for each individual.

Audiological assessment

After screening, data from the most recent pure-tone audiometry were collected, that is, performed with a maximum of three months prior assessment. These audiometries were performed in the Hearing Health service by two independent and properly trained speech therapists. Audiometry was used as the gold standard reference for data analysis. Thus, individuals who underwent hearing screening and did not have recent records of pure-tone audiometry in the medical record were discarded from analysis.

In this study, it is noteworthy that hearing screening aimed to identify individuals with disabling hearing losses, that is, individuals whose average hearing thresholds in the frequencies of 500, 1000, 2000, and 4000 Hz were greater than 40 dB HL in the best ear[1].

Analysis of results

The sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) of screening instruments were calculated in relation to the results of pure-tone audiometry. The Kappa index was used as indicator of concordance between the results of pure-tone audiometry and screening instruments with the following classification: almost perfect (k = 0.81 to 1); substantial (k = 0.61-0.80); moderate (k = 0.41-0.60); regular (k = 0.21 to 0.40); small (k = 0 to 0.20); and poor (k = <0)[22]. The significance level of 5% was adopted.

RESULTS

The sample consisted of 80 individuals (28 men - 35%; 52 women - 65%) aged between 18 and 94 years old (55.18 ± 20.21). Out of these, 37 (46.25%) were aged over 60 years old and 43 (53.75%) between 18 and 59 years old. Audiologically, 21 individuals (26.25%) had bilateral normal hearing and 59 (73.75%) had hearing loss, being unilateral (n = 4), bilateral symmetric (n = 41), and asymmetric (n = 14). Thus, out of the total of 80 participants, 43 (53.75%) had disabling hearing loss. Having as reference the 160 ears of the 80 participants (Table 1), it was observed that 47 ears (29.78%) exhibited normal audiometric thresholds and 113 (70.62%) exhibited some type and degree of sensorineural or mixed-type hearing loss. No conductive hearing loss was found.

Table 2 presents the results on the occurrence of "pass" and "fail" obtained through the hearing screening instruments used and their relationship with the results of pure-tone audiometry (gold standard). It is noteworthy that, in this case, the analysis was performed for each individual.

Sensitivity, specificity, negative predictive values, positive predictive values, and the accuracy of instruments were subsequently calculated (Table 3).

The degree of concordance defined by Kappa index between pure-tone audiometry and hearing screening tests is shown in Table 4.

Table 1. Characterization of the hearing of participants by ear (n = 160)

Type	Degree*	Right ear		Left ear		Total	
		n	%	n	%	n	%
Normal	Normal	23	14.375	24	15	47	29.375
	Total	**23**	**14.375**	**24**	**15**	**47**	**29.375**
Sensorineural	Mild	08	5.00	10	6.25	18	11.25
	Moderate	18	11.25	14	8.75	32	20.00
	Severe	09	5.625	13	8.125	22	13.75
	Profound	09	5.625	09	5.625	18	11.25
	Total	**44**	**27.5**	**46**	**28.75**	**90**	**56.25**
Mixed	Mild	02	1.25	0	0	02	1.26
	Moderate	05	3.125	0	0	05	3.13
	Severe	06	3.75	07	4.375	13	8.08
	Profound	0	0	03	1.875	03	1.87
	Total	**13**	**8.125**	**10**	**6.25**	**23**	**14.375**

Table 2. Comparison of the results of hearing screening and pure-tone audiometry (n = 80)

		Pure-tone audiometry – Quadritonal mean*					
		≤ 40 dB NA		≥ 41 dB NA (hearing loss)		Total	
		n	%	n	%	n	%
MoBASA	Pass	28	35.00	5	6.25	33	41.25
	Fail	9	11.25	38	47.50	47	58.75
	Total	**37**	**46.25**	**43**	**53.75**	**80**	**100**
Telehealth	Pass	11	13.75	0	0	11	13.75
	Fail	26	32.50	43	53.75	69	86.25
	Total	**37**	**46.25**	**43**	**53.75**	**80**	**100**
HHIE-S	Pass	17	21.25	4	5.00	21	26.25
	Fail	20	25.00	39	48.75	59	73.75
	Total	**37**	**46.25**	**43**	**53.75**	**80**	**100**

*Average hearing thresholds at frequencies of 500, 1000, 2000, and 4000 Hz
Caption: MoBASA: Mobile-based Affordable Screening Audiometer; HHIE-S: electronic version of the Auditory Handicap Questionnaire for the Elderly Screening Version

Table 3. Calculation of sensitivity, specificity, positive predictive values, and negative predictive values of the hearing screening instruments compared with the pure-tone audiometry of the total sample

Trials	Sensitivity (%) (95% IC)	Specificity (%) (95% IC)	PPV (%) (95% CI)	NPV (%) (95% CI)
MoBASA	88.30 (0.75;0.94)	75.68 (0.60;0.86)	80.85(2.03;6.48)	84.85 (0.06;0.35)
Telehealth audiometer	100.00 (0.92;1)	29.73 (0.17;0.45)	62.32 (1.15;1.75)	100.00 (-)
HHIE-S	90.70 (0.78;0.96)	45.95 (0.31;0.61)	66.10 (1.23;2.29)	80.95 (0.07;0.54)

Caption: MoBASA: Mobile-based Affordable Screening Audiometer; HHIE-S: electronic version of the Auditory Handicap Questionnaire for the Elderly Screening Version; PPV: positive predictive value; NPV: negative predictive value, CI: confidence interval

Table 4. Kappa concordance between the results of pure-tone audiometry (PTA) and results of different hearing screening procedures.

Tests	Crude concordance rate	Kappa concordance	CI 95%	*p* value
MoBASA	75.7%	0.645	0.427-0.863	<0.001
Telehealth audiometer	29.7%	0.313	0.153-0.472	<0.001
HHIE-S	45.9%	0.378	0.178-0.577	<0.001

Caption: MoBASA: Mobile-based Affordable Screening Audiometer; HHIE-S: electronic version of the Auditory Handicap Questionnaire for the Elderly Screening Version; CI: confidence Interval

Based on the results shown in Tables 3 and 4, a high level of sensitivity, specificity, PPV, and NPV was observed, as well as a Kappa value indicating substantial concordance between the results of pure-tone audiometry and the MoBASA application. Regarding the Telehealth audiometer and the HHIE-S, analyzes showed high sensitivity and low specificity with regular concordance by Kappa index.

DISCUSSION

The results of this study using three low-cost hearing screening instruments compared to the gold standard diagnostic procedure, that is, pure-tone audiometry, showed that the MoBASA app for smartphones is an accurate method for hearing screening in adults and the elderly. In contrast, the HHIE-S questionnaire and the TS audiometer presented specificity and PPV of less than 75%, which limits their use in hearing screening for adults and the elderly, as the false-negative rate is high.

This finding is highly correlated with values greater than 75% for sensitivity and specificity of the MoBASA application. This criterion was also observed only in the sensitivity of the HHIE-S questionnaire and of the TS audiometer, since both presented values below 50% for specificity. This result shows reduced accuracy of these instruments in the identification of hearing loss, which can create difficulties in the assessment and referral of these individuals.

The specificity of 29.73% found for the TS in the present study is not in agreement with the literature[5], which reported sensitivity and specificity of 95.5% and 90.4%, respectively, for this instrument. The differences with data from the present study may have occurred due to the different methodologies employed. In hearing screening, another study with the TS audiometer[5] used a pure-tone threshold of 25 dB HL, that is, the reference used for the "pass x fail" criterion was lower than that of the present study at the thresholds of 500, 1000, 2000, and 4000 Hz. In addition, the authors calculated the sensitivity and specificity in relation to the number of ears tested. In the present study, although the fail criterion in screening with the TS audiometer was related to frequency and ears, specificity was calculated in relation to the participant's best ear, that is, in relation to the individual and following the criterion of

disabling hearing loss[1]. This increased the number of false negatives and decreased the value of specificity, as well as the PPV. On the other hand, the negative predictive value (NPV) for the TS audiometer was expected since the less sensitive the test, the lower its NPV.

Regarding the HHIE-S, the sensitivity and NPV found in the present study (Table 3) were high. Similar results to the present study were reported when the HHIE-S score greater than eight was used to identify losses greater than 40 dB HL, as in the study by Tomioka et al.[23] (sensitivity = 81.3%; NPV = 95.4%) and Diao et al.[24] (sensitivity = 74.5%; NPV = 86.1%). On the other hand, these same authors found higher values for specificity equal to 77.5%[23] and 100%[24]. The accuracy of HHIE-S as a screening instrument has been analyzed in other national[7,25] and international[26,27] studies. However, the criteria adopted for determining altered hearing in such studies were thresholds greater than or equal to 25 dB HL, making direct comparison with the results of the present study unfeasible.

In this study, we opted for the application of HHIE-S in an online format to privilege the administration of this procedure remotely. However, it was observed that 13 (16.35%) participants, due to illiteracy (n = 11, 13.75%) and inability to handle the computer (n = 2, 2.5%), needed assistance from the evaluator, who read the questions and answered the options of the HHIE-s, marking the ones chosen by the individual. Thus, although HHIE-S is known for its brevity and simplicity[6,22], questions on literacy and digital literacy should be considered and deserve further investigation to facilitate and expand the self-administration of this instrument via the internet in Brazil.

The use of hearing screening tests, especially those performed using smartphone applications involving digits-in-noise tests[10,14] demonstrated the advantage of making the moment of hearing screening more environmentally friendly. This aspect is not proposed in the MoBASA application or in the TS. In addition, the use of smartphones has been advantageous in comparison to the need to use computers, tablets, and/or netbooks. If projecting a hearing screening instrument for use on a large scale by other health professionals, its availability as an application would make it easier to access and to be used.

Another point to be highlighted is that the MoBASA application was tested in free-field as opposed to the TS audiometer. Possibly since the sample of this study predominantly had bilateral hearing loss, a greater number of false negatives did not occur. If the objective of assessment is the identification of unilateral hearing loss, it is not advisable to use MoBASA as its stimuli are not calibrated for this testing situation. Further research is needed in order to test the use of different headphones and also to perform their acoustic calibration. On the other hand, the measurement of the TS audiometer is programmed to be applied with headphones, making it advantageous in comparison to MoBASA in this aspect, mainly because it allows the use of a low-cost headset when compared to those used in audiological diagnosis, such as the TDH-39 earphone.

The variability of results in the literature compared to the screening tests of this study is explained by the different methodologies used, including the use of different thresholds and procedures for screening and differences in the criteria for defining hearing loss. The better specificity pointed out in the research in question can be justified by the criteria of normality adopted by each study, as an increase in the occurrence of false positives in studies in which the authors used lower auditory thresholds can be perceived possibly due to the influence of noise in screening rooms that are not acoustically treated. This is a factor highlighted as a challenge by researchers who try to study headphones with noise attenuators for use in these hearing screening environments[15].

Both the MoBASA application and the TS audiometer were developed to be administered by an evaluator. Although brief training is sufficient to handle these instruments, there is still a need for human resources to administer the procedure, which increases the cost of screening. Thus, it is also interesting to study other procedures that are self-administered, as is the case, for example, of applications such as uHear[13,15] and the digit-in-noise test[10,15].

A fact highlighted by Kelly et al.[15] in their study was that the familiarity of individuals, even the elderly, with tablets and smartphones can contribute to the use of these as instruments for hearing screening, especially if they present few instructions.

The present study had some limitations. The first concerns the selection of participants from a public hearing health service, which was not random. This may have included bias due to the greater likelihood that those who volunteered to participate had hearing problems and were more concerned with their hearing. Further research in different populations, especially in asymptomatic populations from Basic Health Units is necessary to expand and understand the applicability of the use of these hearing screening methods.

Another limitation refers to the possible introduction of order bias, since the order in which the screening procedures were conducted was not random or counterbalanced. This was not possible in this study given the logistics and places available within the hearing health service to conduct the research, besides the fact that the researchers remained blind to the results obtained from each participant in each procedure.

Another point that can be understood as a limitation but does not invalidate the results of this study is that the pure-tone audiometry (gold standard) was not performed on the same day of the application of the three hearing screening instruments. This was due to the logistical infeasibility of the SUS hearing health service unit where the research was performed. Thus, pure-tone audiometry was performed up to three months prior to the date of application of the hearing screening instruments. This point does not invalidate the results since most (70.62%) of the individuals included in the study sample had permanent disabling hearing loss. This data is justified by the fact that the participants were mostly elderly (46.25%) and have been recruited in a SUS hearing health service unit, which receives greater demand from individuals who are candidates for the use of personal sound amplification products (PSAP).

When making the choice of the hearing screening procedure to be adopted, the cost-benefit ratio of the procedure and its validity must be taken into account. Procedures that have a high occurrence of false negatives as well as the occurrence of false positives can increase the costs of hearing health programs

for adults and the elderly, since they end up not accomplishing their role in the identification of hearing loss.

This study presents low-cost hearing screening instruments, two of which were developed in Brazil, in order to verify their accuracy as hearing screening or auditory screening instruments, without the intention to replace complete audiological assessment. Evidence showed that possibly the MoBASA application can be used by primary care professionals as a screening step prior to decision-making for referral to specialized care, directly contributing to the improvement of the Hearing Health Care Network for the population.

One study[28] compared eight different devices currently available for hearing screening (Shoebox, HearX, Sentiero, SmarTone, KUDUwave, Interacoustics Titan, Grason-Stadler audioscreener, and Maico ERO Scan) in order to identify the pros and cons of each technology and how these have been used in places with limited economic resources. The authors compared the characteristics of software and hardware, hardware mobility, ease of use and training requirements, data storage, technical support, and financial considerations. The authors concluded that there are options available for low- and middle-income countries, but there is still a need for science to thrive in favor of accessible, sustainable, and portable technologies.

CONCLUSION

MoBASA proved to be an accurate method for hearing screening of individuals with disabling hearing loss in adults and the elderly.

The HHIE-S and the Telehealth audiometer, although having sensitivity above 90%, had low specificity, which limits them in the use of hearing screening, as they can generate a higher rate of false negatives.

ACKNOWLEDGEMENTS

The researchers would like to thank the administrative and technical team of the Center SUVAG- RN, where the research was carried out for the availability of physical spaces and access to research subjects.

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Author contributions

SAB participated in the idealization of the study, collection, data analysis and interpretation, and writing of the article; BSBC, RNP, TFL, and JDJ participated in data collection, tabulation, and analysis; SAB and DVF participated as advisors in the idealization of the study, analysis, data interpretation, and writing of the article; DMSB e RAMV participated in the idealization of the study, development, and analysis of data from the electronic version of the HHIE-S; and EAL participated in the idealization, development, training, calibration, and analysis of the technical data of the Mobile-based Affordable Screening Audiometer (MoBASA) application and the Telehealth audiometer.