Title
Automated Audiometry Using Apple iOS-Based Application Technology

Journal
Otolaryngology, 149(5)

ISSN
0194-5998

Authors
Foulad, Allen
Bui, Peggy
Djalilian, Hamid

Publication Date
2013-11-01

DOI
10.1177/0194599813501461

Peer reviewed

Automated Audiometry Using Apple iOS-Based Application Technology

Allen Foulad, Peggy Bui and Hamid Djalilian

Otolaryngology -- Head and Neck Surgery 2013 149: 700 originally published online 20 August 2013
DOI: 10.1177/0194599813501461

Original Research—General Otolaryngology

AMERICAN ACADEMY OF OTOLARYNGOLOGY–HEAD AND NECK SURGERY FOUNDATION

Otolaryngology–
Head and Neck Surgery
149(5) 700–706

DOI: 10.1177/0194599813501461
http://otojournal.org
SAGE

Automated Audiometry Using Apple iOS-Based Application Technology

Allen Foulad, MD[1], Peggy Bui[2], and Hamid Djalilian, MD[1]

Sponsorships or competing interests that may be relevant to content are disclosed at the end of this article.

Abstract

Objective. The aim of this study is to determine the feasibility of an Apple iOS-based automated hearing testing application and to compare its accuracy with conventional audiometry.

Study Design. Prospective diagnostic study.

Setting. Academic medical center.

Subjects and Methods. An iOS-based software application was developed to perform automated pure-tone hearing testing on the iPhone, iPod touch, and iPad. To assess for device variations and compatibility, preliminary work was performed to compare the standardized sound output (dB) of various Apple device and headset combinations. Forty-two subjects underwent automated iOS-based hearing testing in a sound booth, automated iOS-based hearing testing in a quiet room, and conventional manual audiometry.

Results. The maximum difference in sound intensity between various Apple device and headset combinations was 4 dB. On average, 96% (95% confidence interval [CI], 91%-100%) of the threshold values obtained using the automated test in a sound booth were within 10 dB of the corresponding threshold values obtained using conventional audiometry. When the automated test was performed in a quiet room, 94% (95% CI, 87%-100%) of the threshold values were within 10 dB of the threshold values obtained using conventional audiometry. Under standardized testing conditions, 90% of the subjects preferred iOS-based audiometry as opposed to conventional audiometry.

Conclusion. Apple iOS-based devices provide a platform for automated air conduction audiometry without requiring extra equipment and yield hearing test results that approach those of conventional audiometry.

Keywords

audiometry, hearing, test, automated, iOS, iPhone, iPod, iPad, audiogram

Received January 16, 2013; revised July 15, 2013; accepted July 24, 2013.

Automated audiometry is a valuable method for assessing hearing loss in settings with limited access to audiology personnel. This automated modality uses computer-based algorithms to replicate standard protocols used by audiologists for performing air conduction and bone conduction hearing testing. Several reports have demonstrated that hearing test threshold values achieved using automated audiometry are similar in reliability compared with results obtained by an audiologist using conventional manual audiometry.[1-4] Automated audiometry is useful for screening programs as well as for promptly providing otolaryngologists with supplemental data during the initial evaluation of patients with otologic complaints. Following preliminary assessment, more comprehensive hearing testing can be performed with referral to an audiologist.

The technology of automated audiometry devices has been significantly improving. Current devices, such as the Otogram (Ototronix, Houston, Texas), offer a user-friendly interface, perform both air conduction and bone conduction testing, and use masking. Advancements in computers enable effortless deployment of numerous software solutions with complex algorithms, while Internet connectivity provides a means to transfer hearing test results to remote locations. Methods have also been described that predict testing accuracy during the automated hearing test.[5,6] As automated audiometry becomes more standardized, the devices will continue to become more accurate, portable, and economical.

A promising avenue for automated audiometry is the deployment of this technology on commonly available portable electronics. Apple iOS-based devices (Apple Inc, Cupertino, California), such as iPhone smartphones and iPod touch music players, provide an ideal platform because they support headsets and the development of custom software applications. In addition, these Apple devices are standardized with similar hardware and software components, and thus a single application can potentially be universally

[1]Department of Otolaryngology-Head and Neck Surgery, University of California, Irvine, Orange, California, USA
[2]University of California, Irvine, Orange, California, USA

Corresponding Author:
Hamid Djalilian, MD, Department of Otolaryngology-Head and Neck Surgery, University of California, Irvine Medical Center, Building 56, 101 The City Drive South, Orange, CA 92868, USA.
Email: hdjalili@uci.edu

shared with all iOS-based device models. These devices are currently widespread worldwide and easily accessible.

This study aims to develop and evaluate the feasibility of an iOS-based hearing test application that performs pure-tone audiometry and is compatible with the Apple iPhone, iPod touch, and iPad. The accuracy of this automated testing modality is measured by comparing the results using the application to results obtained using conventional audiometry by an audiologist.

Methods

This clinical prospective study was reviewed and approved by the institutional review board at the University of California, Irvine.

Subjects

All subjects were approached and recruited in the University of California, Irvine Medical Center neurotology clinic during their standard appointment for hearing evaluation. Recruitment days were selected such that the required staff and equipment were available during the span of the entire clinic day and all patients would be able to be consecutively approached. Patients were excluded from the study if they were unable to follow simple commands, were unable to remain alert during the duration of hearing test, were unable to press the virtual buttons on the touch-screen device, or exhibited signs of active ear drainage. In addition, patients were excluded if they had congenital or acquired deformities of the ear that prevented secure insertion of an intraconchal earbud. A total of 42 subjects were included in the study during 2012 and 2013.

iOS Automated Audiometry Application

An iOS-based software application for the Apple iPhone, iPod touch, and iPad was developed to perform pure-tone air conduction hearing testing in an automated fashion. The application, EarTrumpet (PraxisBiosciences, Irvine, California), was released and made accessible as a download through the Apple iTunes store in 2010. The application uses an algorithm to determine hearing threshold values via a 10-dB down and 5-dB up modified Hughson-Westlake method, as recommended by the British Society of Audiology.[7] The test tones are 0.8 seconds in duration, while the silent interval between tones randomly varies between 1 to 2 seconds. Masking is automatically performed if the difference between threshold values of the 2 ears is equal to or greater than 35 dB. The masking sound is composed of a narrow-band noise centered at the frequency being tested with a slope of –40 dB/octave. The masking sound is played in the better hearing ear at an intensity of 35 dB below the intensity of the pure tone being tested and restricted to a maximum intensity of 60 dB. At the conclusion of the test, an audiogram is displayed, which can be saved on the device and emailed (**Figure 1**).

The iOS-based hearing test was designed and calibrated to be used with the intraconchal headset included with the Apple devices. Calibration was performed by measuring the decibel level of pure-tone sound outputted from the device at various frequencies and volume levels using a sound meter (Modular Precision Sound Analyzer Type 2260; Brüel & Kjær A/S, Nærum, Denmark). A 2.5-cm-long tube was used to connect the earbud to the microphone of the sound meter to mimic the length of the ear canal and maintain a constant setup. A regression was fit to the data to provide conversion between device volume level and output dB level for each frequency supported by the hearing test. The equation was normalized to the appropriate dB hearing level (HL) by obtaining the hearing threshold values of 5 subjects using the initial equation and comparing the data with the threshold values obtained from conventional audiograms. This final equation was used by the hearing testing algorithm to provide test tones with appropriate dB HL.

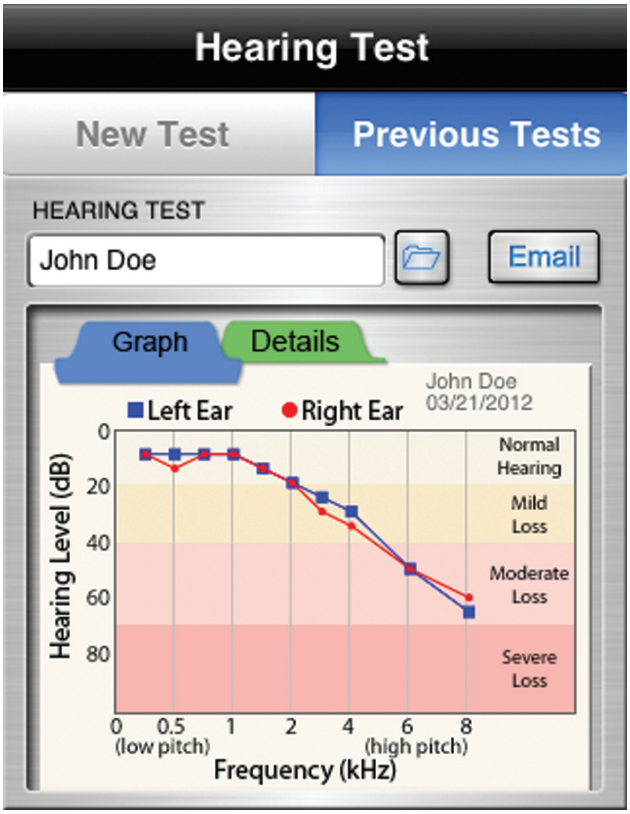

Figure 1. Audiogram generated by the EarTrumpet iOS-based automated hearing test.

iOS Device Compatibility Testing

To assess for device variations, the standardized sound output of a comprehensive list of various Apple iPhone, iPod touch, and iPad device models in combination with various Apple headsets was measured using an audiometer. A custom application was developed to output pure-tone sounds at a volume gain of 0.025 (maximum 1.0) as specified within the low-level application coding. All devices were standardized by setting the user-controllable volume to 75% of its maximum limit. The output level (dB) of the pure-tone sound corresponding to each hearing test frequency was measured using a sound meter with a connecting tube, similar to the apparatus previously described for sound output calibration. The standardized sound output (dB) of the various Apple device and headset combinations was compared in table format.

Hearing Threshold Measurements

All subjects underwent pure-tone hearing testing using 3 methods: (1) conventional manual audiometry with an audiologist, (2) automated iOS-based hearing testing in a sound booth, and (3) automated iOS-based hearing testing in a quiet room. Each method uses pulsed tones and starts the hearing test on the ear with better hearing if asymmetric loss is present. Hearing threshold values are then measured using a 5-dB step size for a comprehensive set of frequencies (250, 500, 750, 1000, 1500, 2000, 3000, 4000, 6000, and 8000 Hz). Hearing threshold values describe the lowest measured decibel that a subject can hear at the frequency tested. The first frequency tested is 1000 Hz, and then the frequency is progressively advanced to the next higher frequency until 8000 Hz is reached and tested. Then 750 Hz is tested, and the next lower frequency is progressively tested until 250 Hz is reached.

Conventional hearing evaluation for all patients was performed using the modified Hughson-Westlake method by the same AuD audiologist with more than 15 years of experience. The patients were enclosed in a double-walled sound booth (ISO 6189 compliant) and were tested using a GSI 16 Audiometer (Grason-Stadler, Eden Prairie, Minnesota) equipped with insert headphones calibrated under the American National Standards Institute (ANSI) guidelines. The audiologist did not have access to the data from the automated hearing test.

Automated iOS-based audiometry was performed using version 1.1.0 of the EarTrumpet application with either an iPhone or iPod touch. Patients were given the device with the application open and instructed to insert the Apple earbuds in their ears and follow the directions presented by the application. For testing in a quiet environment, the subjects were instructed to take the test in any room that was quiet, such as a bedroom in their residence. They were recommended to avoid environments with even faint noises, such as those generated by the fan of a computer or refrigerator. Individuals who owned an appropriate Apple device were instructed to download EarTrumpet and run the test on their own device. Otherwise, they were loaned either an iPod touch or iPhone.

Preference Survey

After completing all testing, subjects were asked the following 3 questions: (1) Do you prefer manual testing with the audiologist or do you prefer the iOS-based automated testing in a quiet room? No preference is an option. (2) Which testing method do you prefer if the automated test requires a sound booth as well? (3) Please provide the reasons for your preferences.

The survey was administered in person within a confined room or via telephone by a research assistant with no conflict of interest. The preferences of the subjects were categorized as to which hearing modality they preferred, and the open-ended reasons for their preferences were charted.

Data Analysis

The data from the 3 hearing test modalities for all subjects were recorded separately into Excel worksheets. All analyses, including statistical testing and categorization, were performed in an automated fashion using formulas to minimize error and potential bias. In performing the primary analysis, a single ear was selected at random per patient to avoid sample size inflation and maintain more stringent calculations. The difference between corresponding threshold values obtained via manual audiometry and iOS-based automated audiometry were calculated for each frequency and categorized as being within 0 to 5, 0 to 10, 0 to 15, and 0 to 20 decibel ranges. A mean percentage representing the percent of threshold values that fall within each decibel range was calculated, which reflects the correlation between conventional and iOS-based testing. Confidence intervals were calculated at the 95% confidence level using a binomial approximation based on the central limit theorem.[8] A broader and more detailed representation of the data using both ears was tabulated, which included average percentages of the paired threshold differences within the 0 to 5, 0 to 10, 0 to 15, and 0 to 20 decibel ranges for each individual frequency. Conventionally, test-retest threshold values via manual audiometry are considered reliable up to a 10-dB difference, and thus the results within this range are emphasized.[9] For all analyses, data were not included for threshold values that exceeded the maximum sound output of the audiometry devices. All data entering and analyses were performed by research assistants and a statistician, who have no conflict of interest.

Results

Of the 42 patients who were enrolled in the study, 10 had normal hearing (all thresholds $\leq$20 dB), whereas 32 had some level of hearing impairment (**Table 1**). A total of 482 threshold values were within the hearing impairment range. The patients included both sexes (23 male, 19 female) and ranged in age from 20 to 85 years (mean, 58 years). A total of 28 subjects owned or had access to an Apple iPhone, iPod touch, or iPad.

The sound intensity output of a wide array of Apple device and headset combinations was found to be similar (**Table 2**). The maximum intrafrequency difference in sound intensity between the various devices, while keeping the headset constant, was 1 dB. However, when also including 2 different Apple headsets in the comparison, there was a maximum intrafrequency difference in sound intensity of 4 dB.

Table 3 compares the threshold values obtained using manual audiometry and iOS-based audiometry as evaluated for the primary analysis. On average, 96% (95% confidence interval [CI], 91%-100%) of the threshold values obtained using the automated test in a sound booth were within 10

Table 1. Categorization of the hearing threshold values for both ears of all subjects participating in the study, as determined by conventional audiometry.[a]

Decibels	250 Hz	500 Hz	750 Hz	1 kHz	1.5 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
0-20	48	45	47	48	37	37	31	31	31	30
25-50	28	30	29	27	36	31	31	24	21	20
55-80	11	12	11	11	13	16	20	27	24	24
85-100	0	0	0	1	1	3	4	5	9	13

[a]Threshold values that exceeded the limits of the testing equipment were not included in the study and thus excluded from the table.

Table 2. Standardized pure-tone sound output, in decibels, of various Apple device and headset combinations for the commonly used frequencies in audiometry.[a]

Device	250 Hz	500 Hz	750 Hz	1 kHz	1.5 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
Headset MA814LL										
iPhone 3G	72	74	71	67	60	55	55	56	56	45
iPhone 3GS	71	74	71	67	60	54	55	55	56	44
iPhone 4	71	74	70	67	60	54	55	55	56	44
iPhone 4S	71	74	71	67	60	55	55	55	56	45
iPod Touch 2G	71	74	70	67	60	54	54	55	56	45
iPod Touch 3G	71	74	71	67	60	55	54	55	56	45
iPod Touch 4G	72	74	71	67	60	55	55	55	56	45
iPad 1	72	74	71	67	60	55	54	55	56	45
iPad 2 Wifi	72	74	71	67	60	55	55	55	56	45
iPad 2 GSM	72	74	71	67	60	55	54	55	56	45
Headset MB770G										
iPhone 3G	71	72	70	66	60	56	58	54	56	44
iPhone 3GS	71	71	69	65	60	55	57	54	55	44
iPhone 4	71	72	69	65	60	55	57	54	55	44
iPhone 4S	71	72	69	65	60	55	57	54	55	44
iPod Touch 2G	71	72	69	66	60	55	57	54	55	44
iPod Touch 3G	71	72	69	66	60	56	57	54	55	44
iPod Touch 4G	71	72	69	66	60	56	57	54	55	44
iPad 1	71	72	69	65	60	55	57	54	55	44
iPad 2 Wifi	71	72	69	66	60	55	58	54	55	44
iPad 2 GSM	71	72	69	66	60	55	57	54	55	44

[a]The data are subdivided by the 2 Apple headsets evaluated, model MA814LL (iPhone stereo headset) and the newer model MB770G (earphones with remote and microphone).

dB of the corresponding threshold values obtained using conventional audiometry. When the automated test was performed in a quiet room, 94% (95% CI, 87%-100%) of the threshold values were within 10 dB of the threshold values obtained using conventional audiometry.

Table 4 compares the threshold values obtained using manual audiometry and iOS-based automated audiometry, categorized by frequencies. The paired threshold value differences between the iOS-based automated hearing test taken in a sound booth and manual audiometry were never greater than 20 dB. However, the paired threshold values approached a maximal difference of 25 dB when comparing the automated test performed in a quiet room and conventional audiometry.

Five patients had asymmetric hearing loss, with a total of 31 frequencies having greater than a 30-dB difference between paired ears and requiring masking. A subanalysis including only the masked frequencies revealed that 100% of the threshold values obtained using the automated test, whether performed in a sound booth or quiet room, were within 10 dB of the corresponding threshold values obtained using manual audiometry.

All patients preferred iOS-based audiometry if a clinic visit was not required for the automated testing and the test could be taken in a quiet room of their choosing. When standardizing all testing modalities by requiring an outpatient clinic visit, 38 of 42 (90%) patients preferred iOS-based audiometry compared with conventional audiometry. Reasons

Table 3. Distribution of threshold differences between manual audiometry and automated iOS-based audiometry for 1 randomly selected ear per patient.[a,b]

Threshold Difference	M vs iOS-SB	M vs iOS-QR	iOS-SB vs iOS-QR
0- to 5-dB difference	80.1 (68.0-92.2)	79.2 (67.0-91.5)	88.3 (78.6-98.0)
0- to 10-dB difference	96.5 (90.9-100)	94.1 (86.9-100)	96.7 (91.2-100)
0- to 15-dB difference	99.3 (96.7-100)	97.5 (92.7-100)	100 (100-100)
0- to 20-dB difference	100 (100-100)	99.5 (97.4-100)	100 (100-100)

Abbreviations: iOS-QR, iOS automated hearing test performed in a quiet room; iOS-SB, iOS automated hearing test performed in a sound booth; M, manual audiometry.
[a]Data are listed as mean percentages (95% confidence interval).
[b]For all testing modalities, no threshold differences exceeded 25 dB.

Table 4. Distribution of threshold differences between manual audiometry and automated iOS-based audiometry for both ears, by frequency.

Threshold Difference and Device	250 Hz	500 Hz	750 Hz	1 kHz	1.5 kHz	2 kHz	3 kHz	4 kHz	6 kHz	8 kHz
0- to 5-dB difference										
M vs iOS-SB	66	74	80	67	67	82	82	82	58	79
M vs iOS-QR	67	71	72	70	73	81	81	81	62	75
iOS-SB vs iOS-QR	75	75	84	88	88	96	97	95	95	92
0- to 10-dB difference										
M vs iOS-SB	96	95	98	92	95	96	95	96	88	94
M vs iOS-QR	87	91	96	93	94	94	95	94	87	92
iOS-SB vs iOS-QR	88	90	95	96	96	100	97	99	100	96
0- to 15-dB difference										
M vs iOS-SB	100	100	100	96	96	99	100	99	97	96
M vs iOS-QR	96	99	98	99	98	98	98	99	97	94
iOS-SB vs iOS-QR	98	99	99	100	99	100	100	99	100	99
0- to 20-dB difference										
M vs iOS-SB	100	100	100	100	100	100	100	100	100	100
M vs iOS-QR	99	100	100	100	100	100	100	100	100	97
iOS-SB vs iOS-QR	100	100	100	100	100	100	100	100	100	100

Abbreviations: iOS-QR, iOS automated hearing test performed in a quiet room; iOS-SB, iOS automated hearing test performed in a sound booth; M, manual audiometry.
[a]Data are listed as mean percentages.
[b]For all testing modalities, no threshold differences exceeded 25 dB.

for favoring iOS-based audiometry included being simpler, more comfortable, less intimidating, more convenient, and more controllable. Two subjects had no preference between the testing modalities. The 2 subjects who preferred manual audiometry expressed reasons that included familiarity with the conventional method and the perception that results would be better with the conventional method.

Discussion

This study evaluated a software application, EarTrumpet, which provides automated hearing testing functionality to iOS-based devices such as the Apple iPhone, iPod touch, and iPad. The application can be downloaded to these devices and requires no extra hardware. The automated hearing test results obtained using the iOS-based application were similar to the hearing test results obtained using conventional audiometry.

The similarities between the Apple iPhone, iPod touch, and iPad enable a single software solution for multiple devices. In addition to sharing the same operating system, these iOS-based devices are equipped with comparable sound-processing hardware. Accordingly, our data revealed that the pure-tone sound intensity generated by various Apple device and headset combinations at a standardized volume setting was within 4 dB. Although further work with a larger sample size is favorable, these results are promising for straightforward development and deployment of a hearing testing application for numerous Apple devices.

The accuracy of the EarTrumpet automated hearing test is similar to previously described automated testing methods and also comparable to conventional audiometry test-retest results. On average, 96% of the threshold values obtained using iOS-based automated audiometry in a sound booth were within 10 dB of the corresponding threshold values obtained using conventional audiometry (95% CI, 91%-100%). Comparably, Ho et al[3] revealed that the paired results between the automated Otogram and manual audiometry were within 10 dB for 94% of the threshold values. They also concluded that 93% of the threshold values for pure-tone manual audiometry were within 10 dB of the threshold values obtained after retesting with the same conventional method. Swanepoel et al[4] reported more favorable results by demonstrating that 98% of the paired threshold values using test-retest manual audiometry were within 10 dB. Similar to the current study, Van Tasell and Folkeard[10] performed automated audiometry using an iPad, albeit equipped with standard audiometry headphones, and demonstrated that the tablet device yielded threshold values similar to the results obtained by manual audiometry (mean difference, 4.1 dB). With growing evidence of the comparable accuracy of automated audiometry, such automated systems are finding a greater role in the armamentarium of clinicians.

A notable finding of this study is the use of the iOS-based automated hearing test without a sound booth. When the automated test was simply performed in a quiet room, 94% of the threshold values were within 10 dB of the threshold values obtained using conventional audiometry in a sound booth (95% CI, 87%-100%). Although the accuracy of the threshold values is decreased when a sound booth is not used, the difference is minimal. Thus, under certain circumstances, an adequately quiet room may be a reasonable testing environment if a sound booth is not accessible.

An iOS-based automated hearing test can be easily administered by health care professionals with minimal time commitment and cost. Such an application can potentially be beneficial as a general screening tool, as well as provide useful data when evaluating patients who present with specific otologic complaints when a conventional audiogram is not immediately available. More comprehensive audiologic evaluation can then be performed in select cases. Furthermore, the portability of the device enables testing in remote and medically underprivileged regions.

Another advantage of the iOS-based hearing test is the technology's easy accessibility to the patient population. In the setting of concern for subjective hearing loss, whether acute or chronic, individuals may deemphasize the importance of seeking professional care due to cost or time restrictions. These individuals would potentially be more likely to use a convenient screening test on a mobile application and follow up with a medical professional if the results indicated an abnormality. More formal evaluation by a medical practitioner can then diagnose the pathology and provide appropriate treatment as needed. Individuals already diagnosed with hearing impairment, especially sudden sensorineural hearing loss, may find added comfort in being able to track their hearing at home on a more regular basis.

Although portable electronics have a potential role for hearing evaluation, various limitations must be considered. The general public must be advised that despite the application's demonstrated accuracy, a medical practitioner is fundamental for ensuring accurate diagnosis and proper treatment. In addition, the technology is currently restricted to air conduction audiometry, and thus comprehensive evaluation may be limited without access to other testing modalities such as bone conduction and speech audiometry. Consideration must also be given to the subgroup of patients requiring masking. While there was excellent agreement in masked threshold values between the automated and manual testing modalities in the current study, the sample size of this subgroup was limited. Despite the current limitations, we hope that the demonstrated feasibility and accuracy of the application will motivate further work to refine the technology.

The proposed Apple iOS-based application offers an easily accessible, automated method for air conduction audiometry that yields results similar to conventional audiometry. The application technology does not require specialized hardware and can potentially supplement hearing testing in settings with limited resources or space.

Acknowledgments

We thank Alicia Traktman, AuD, at UC Irvine Medical Center for her assistance in performing the conventional audiometry testing. We also thank Brian Wong, MD, PhD, and William Armstrong, MD.

Author Contributions

Allen Foulad, design of the study, development of the iOS-based application, drafting and revision of the article; **Peggy Bui**, acquisition and analysis of the data, revision of the article; **Hamid Djalilian**, design of the study and revision of the article.

Disclosures

Competing interests: Hamid Djalilian assisted in development of the EarTrumpet technology and holds a license of co-inventorship for the EarTrumpet technology. Allen Foulad performed the programming and development of the EarTrumpet application. In addition, he is a consultant for the EarTrumpet application technology and receives royalties. He also holds a license of co-inventorship for the EarTrumpet technology. Peggy Bui is associated with the University of California, Irvine but has no direct conflict of interest with the EarTrumpet application.

Sponsorships: None.

Funding source: A grant from the UC Irvine Department of Otolaryngology, Head and Neck Surgery was obtained to aid in carrying out the method sections of the study.

References

1. Jerlvall L, Dryselius H, Arlinger S. Comparison of manual and computer-controlled audiometry using identical procedures. *Scand Audiol*. 1983;12:209-213.
2. Picard M, Ilecki HJ, Baxter JD. Clinical trial of BOBCAT: 1st report on the reliability and validity of computerized pure-tone audiometry [in French]. *Audiology*. 1988;27:234-246.
3. Ho AT, Hildreth AJ, Lindsey L. Computer-assisted audiometry versus manual audiometry. *Otol Neurotol*. 2009;30:876-883.

4. Swanepoel D, Mngemane S, Molemong S, Mkwanazi H, Tutshini S. Hearing assessment—reliability, accuracy, and efficiency of automated audiometry. *Telemed J E Health*. 2010; 16:557-563.
5. Margolis RH, Saly GL, Le C, Laurence J. Qualind: A method for assessing the accuracy of automated tests. *J Am Acad Audiol*. 2007;18:78-89.
6. Margolis RH, Frisina R, Walton JP. AMTAS(®): automated method for testing auditory sensitivity, II: air conduction audiograms in children and adults. *Int J Audiol*. 2011;50:434-439.
7. Recommended procedures for pure-tone audiometry using a manually operated instrument. *Br J Audiol*. 1981;15:213-216.
8. Brown LD, Cai TT, DasGupta A. Interval estimation for a binomial proportion. *Stat Sci*. 2001;16:101-117.
9. Lemkens N, Vermeire K, Brokx JP, et al. Interpretation of pure-tone thresholds in sensorineural hearing loss (SNHL): a review of measurement variability and age-specific references. *Acta Otorhinolaryngol Belg*. 2002;56:341-352.
10. Van Tasell DJ, Folkeard P. Reliability and accuracy of a method of adjustment for self-measurement of auditory thresholds. *Otol Neurotol*. 2013;34:9-15.