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ORIGINAL RESEARCH

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Tools for telehealth: A correlational analysis of app-based hearing testing

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Abstract

Objective: Telehealth evaluation of hearing is rapidly evolving; however, the lack of consensus on the most accurate remote hearing test application has made hearing evaluation complicated. The objective of this study was to evaluate the correlation between the pure tone audiometry results obtained from app-based hearing testing programs and a traditional audiogram.

Methods: A prospective within-subject and between-subject study design was used to correlate audiogram results between app-based hearing programs and a traditional audiogram. All participants completed a traditional audiogram, 1 commercial app-based test (ShoeBox), 2 consumer app-based tests (EarTrumpet and Hearing Test and Ear Age Test [HTEAT]), and a Hearing Handicap Inventory screening version (HHI-S). Testing was conducted in an acoustically controlled environment (traditional) and a quiet room (app-based hearing tests).

Results: A total of 39 participants were enrolled in the study (21 with normal hearing and 18 with hearing loss). In patients with normal hearing, only the commercial hearing testing app (ShoeBox) had a statistically significant pure tone average correlation in both ears with traditional audiometry (Right ear—$r = 0.7$, $p = .005$, Left ear—$r = 0.66$, $p = .001$). Both consumer and commercial apps had statistically significant correlations with both ears in patients with hearing loss (ranging from $r = 0.62$ to $r = 0.9$). Regarding accuracy within 10 dB of the pure tone average of the traditional audiogram of all tested ears, the commercial app-based test was accurate in 94% for all ears (normal and hearing loss), while consumer app-based tests were between 14% and 36% for all ears. The HHI-S indicated no hearing impairment in 95% of those with normal hearing and indicated hearing impairment in 89% of those with hearing loss.

Conclusion: Commercial-grade app-based pure tone audiometry demonstrates overall strong correlation and accuracy with traditional audiometry. The HHI-S

assessment remains a valid and useful tool to predict normal hearing and hearing impairment.

Level of Evidence: 2

KEYWORDS
audiology, hearing loss, screening, telehealth

1 | INTRODUCTION

Pandemic-related and technology-driven changes in healthcare have resulted in drastic changes and unprecedented challenges to care delivery. The negative impacts of hearing loss on communication have been amplified during the pandemic, as patients with hearing loss faced increased difficulty in access to healthcare.[1] Many patients have been hesitant to seek out in-person non-emergent care due to concerns for exposure to COVID-19 and have turned to telehealth options. The COVID-19 pandemic thrust telehealth into the forefront of healthcare delivery with an 845% increase in usage.[2] Otolaryngologists and audiologists have faced significant obstacles in meeting this new demand for remote care. The lack of accurate and reliable audiologic evaluations have proven to be a major factor limiting the utility of telehealth in caring for patients with hearing loss.

Traditional audiological evaluation requires a controlled environment, specialized equipment, and trained professionals. Several promising telehealth applications have been developed for all aspects of audiology. A wide range of auditory rehabilitation services can be provided remotely for patients with hearing aids and cochlear implants.[3] Furthermore, there is growing body of evidence demonstrating the feasibility and utility of telehealth applications in patient education and diagnostic services.[4–8] Application-based hearing assessment programs on electronic devices have become increasingly available over the past decade.[9] These app-based programs can provide a self-administered screening of hearing on a variety of types of devices and operating systems.[10] These apps, while being user friendly and automated in nature, are designed to mimic traditional protocols used by audiologists. The algorithms have grown in complexity to provide air and bone conduction with or without masking. Despite the wide availability of these apps and the relative ease of use, the validity and accuracy of the app-based hearing test results remains a major concern.[11] Widespread use of accurate and validated audiometric applications could lead increase access to and utilization of hearing healthcare, especially for patients in remote locations. The purpose of this study is to evaluate the correlation of commercial and consumer based audiometric applications with traditional audiometry in patients with normal hearing as well as those with hearing loss.

2 | MATERIALS AND METHODS

Prior to initiating any research activities, the Institutional Review Board at the University of Kentucky reviewed and approved the protocol. We sought to prospectively recruit adults over the age of 18 into one of two cohorts: a cohort of participants with normal hearing and a cohort with hearing loss. Upon obtaining informed consent, all patients underwent traditional audiometry to determine cohort assignment. Any participants with two or more pure tone thresholds from 250 to 8000 Hz below 25 dB was placed into the hearing loss cohort. A total of 39 participants were recruited through the University of Kentucky Medical Center Department of Otolaryngology—Head and Neck Surgery. Of those participants 21 had normal hearing and 18 participants had hearing loss.

A total of four hearing tests were administered to each subject including one traditional audiogram and three iOS-based hearing applications conducted through tablets. The order in which the hearing tests were administered was randomized among the participants. Both commercial and consumer-based iOS applications were used. The three iOS applications studies were the Hearing Test and Ear Age Test (HTEAT) version 1.6 (consumer), Ear Trumpet version 1.2.1 (consumer), and SHOEBOX Audiometry Standard Edition version 4.1 (commercial). The Hearing Test and Ear Age Test was selected as it is a widely available application for iOS which is free and provides results which can be exported as either email or text.[11] The Ear Trumpet test was utilized as it has previously been validated with prospective research,[12] tests a broad range of frequencies from 250 to 8000 Hz, was the attention of an ASHA publication, and was available for $3.99 on iOS devices. SHOEBOX was selected as it represents a commercial-grade mobile app-based audiometer, calibrated using American National Standards Institute standards, tests a broad range of frequencies from 250 to 8000 Hz, utilizes noise monitoring, masking, and cloud data storage, and was available for purchase between $2000 and 4100.[9] All iOS applications were administered on an iPad using iOS version 10.3.3. HTEAT and Ear Trumpet were both available for download in the Apple App Store at the time of the study while SHOEBOX Audiometry was obtained directly from the developers and is paid for through a monthly subscription.

HTEAT and Ear Trumpet were administered using BYZ Stereo Over-Ear headphones which were purchased from Amazon.com while SHOEBOX Audiometry was administered using RadioEar DD450 headphones that were sent directly from the company following the initial subscription payment. The RadioEar DD450 headphones were calibrated to the SHOEBOX Audiometry audiometer prior to their use in the study.

All iOS-based hearing tests were administered to subjects outside of a sound booth in a non-acoustically protected room. The purpose of using a room with mild levels of ambient noise was to mimic the

home or primary care environment where the typical examination room has little to no form of acoustic protection. The audiogram was performed by a licensed audiologist using a GSI Audiostar Pro audiometer in a double-walled sound suite with TDH-50 headphones. Hearing was tested at the frequencies between 250 and 8000 Hz via the modified Hughson-Westlake method.

Prior to each testing session subjects were also asked to complete a Hearing Handicap Inventory (HHI-S) Screening Questionnaire for Adults that was embedded in the SHOEBOX Audiometry application. The HHI-S asks 10 questions to the subject regarding the impact of their hearing capabilities on their daily life and is meant to be a quick screening method for hearing loss. The HHI-S scoring interpretation given by SHOEBOX Audiometry on the screen at the end of the questionnaire is as follows: 0–8 = 13% probability of hearing impairment (no handicap), 10–24 = 50% probability of hearing impairment (mild–moderate handicap), 26–40 = 84% probability of hearing impairment (severe handicap).

SHOEBOX Audiometry is considered a commercially available application. The test is adaptive and requires that the users press a green button on the screen immediately after a sound is detected. If no stimulus is heard after the central button has been pressed, users press a red button on the screen. These instructions were explained to each patient by the investigator prior to each testing session and participants voiced understanding of the task. Each testing session was administered under the adult test type. SHOEBOX Audiometry also has the capability to analyze background noise and can detect whether results may be skewed by ambient noise masking. One items that differentiates SHOEBOX Audiometry from other hearing tests is that the stimulus may be repeated at the subject's discretion. For instance, if a user is unsure if he or she can hear a sound, the user can press the central button multiple times to elicit the stimulus and determine if a sound is or is not heard. Like the other two iOS applications, SHOEBOX Audiometry provides an audiogram at the conclusion of the test where the investigator can interpret the results.

The consumer iOS applications tested the same frequencies via different methods. HTEAT uses a simple platform in which the volume of the test is automatically set to a standardized level prior to the start without any form of earphone calibration. All six frequencies are evaluated in both ears in a test that lasts approximately 6 min. During testing, sounds at the varying frequencies were presented in each ear and the subject was instructed to simply press the button on the screen whenever he or she could hear the stimulus. At the end of the test, a graph displaying the results was shown plotting frequency as a function of the intensity level at which the stimulus was heard. To simplify the interpretation of the test, colored lines were displayed horizontally on the graph that demonstrated thresholds that characterize normal hearing, mild hearing loss, moderate hearing loss, and severe hearing loss. Any data point that falls within one of these ranges can thus be easily interpreted as one of these four results.

Ear Trumpet uses a very similar platform in which all six frequencies are tested in each ear and the patient is instructed to press a button on the screen whenever he or she can hear the stimulus. However, unlike HTEAT, Ear Trumpet has the capability to analyze the room for background noise so that test tones are delayed should the hearing test detect excess background noise. Ear Trumpet takes approximately 10 min to administer and provides a graph like HTEAT following the conclusion of the hearing test where data points are plotted and thresholds for normal hearing, mild hearing loss, moderate hearing loss, and severe hearing loss are well-demarcated.

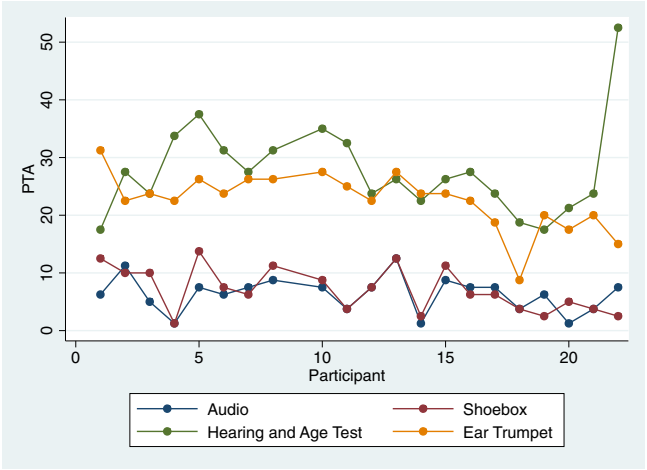

FIGURE 1 Pure tone averages for each participant in the normal hearing group across all for four conditions for the left ear.

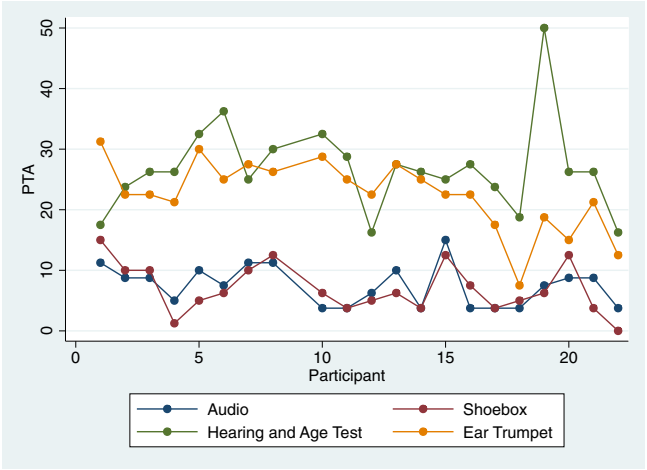

FIGURE 2 Pure tone averages for each participant in the normal hearing group across all for four conditions for the right ear.

Descriptive statistical analysis included threshold data for each app and the audiometer for individual pure tones (250, 500, 1000, 2000, 4000, and 8000 Hz) and four frequency pure tone average (500, 1000, 2000, 4000 Hz). Correlation analysis of thresholds (individual pure tones and PTA) between each app pure tone for each ear and the audiometer results were conducted using Spearman's rank correlation coefficient. We also calculated the accuracy for each app to produce a PTA within 10 dB of the audiogram among all ears of patients with normal hearing and with hearing loss. We also calculated the accuracy of HHI to predict the presence or absence of hearing loss. Data were managed using an Excel spreadsheet (Microsoft,

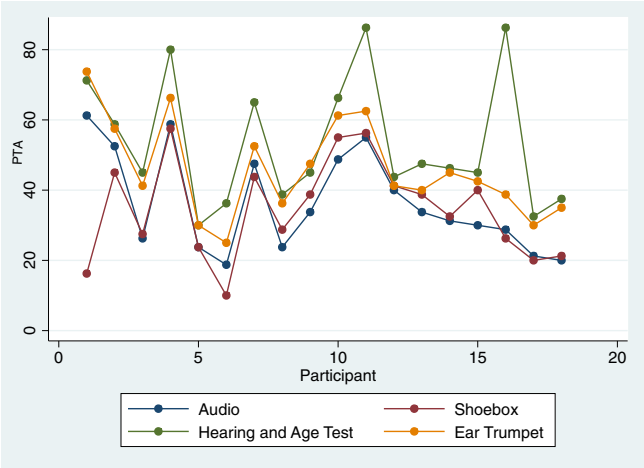

FIGURE 3 Pure tone averages for each participant in the hearing loss group across all for four conditions for the left ear.

FIGURE 4 Pure tone averages for each participant in the hearing loss group across all for four conditions for the right ear.

Redmond, WA, USA), and statistical analyses were performed with Stata (StataCorp, College Station, TX, USA).

3 | RESULTS

A total of 39 participants were recruited into the study (21 with normal hearing and 18 with hearing loss). Of the normal hearing participants, 8 were male and 13 were female and the average age was 31.4 (range from 25 to 51). Of the participants with hearing loss, nine were male and nine were female and the average age was 65.7 (range from 42 to 85). Statistical analysis was performed using Spearman's rank correlation coefficients to evaluate differences across the different audiologic tests among participants with normal hearing and those with hearing loss. Specifically, the strength of correlations between the traditional audiogram and each of the commercial (SHOEBOX) and consumer (Ear Trumpet and HTEAT) iOS-based applications is discussed below. This analysis was performed using pure tone averages (PTA) at 500, 1000 and 2000 Hz. Individual PTAs for each ear across participants for all four tests are displayed for patients with normal hearing in the left ear (Figure 1) and the right ear (Figure 2) and with participants with hearing loss in the left ear (Figure 3) and right ear (Figure 4).

There was a significant difference in the strength of the correlations between the commercially available and consumer iOS applications in normal ears. There was a statistically significant correlation observed between the audiogram and SHOEBOX test results for normal hearing participants in both right ears ($r = 0.7$, $p = .005$) and left ears ($r = 0.66$, $p = .001$). There was similarly statistically significant correlation between the audiogram and SHOEBOX results for participants with hearing loss in both right ears ($r = 0.8$, $p = .0002$) and left ears ($p = .7$, $p = .0015$). The EarTrumpet App did not demonstrate a statistically significant correlation in either normal hearing participants in right ears ($r = 0.43$, $p = .053$) or left ears ($r = 0.33$, $p = .14$). The EarTrumpet App demonstrated a statistically significant correlation in hearing loss participants in right ears ($r = 0.88$, $p = .0001$) and left ears ($r = 0.94$, $p = .0001$). The HTEAT App did not demonstrate a statistically significant correlation in normal hearing participants in either right ears ($r = 0.03$, $p = .91$) or left ears ($r = 0.33$, $p = .14$). HTEAT App demonstrated a statistically significant correlation in hearing loss participants in right ears ($r = 0.62$, $p = .006$) and left ears ($r = 0.79$, $p = .0001$). Frequency specific correlation analyses revealed similar correlation patterns as the PTA analyses.

Regarding the accuracy of the PTA for each test, SHOEBOX was within 10 dB of the audiogram PTA threshold in 94% of for all ears (both normal hearing and hearing loss). EarTrumpet was within 10 dB of the audiogram PTA in 36% for all ears. The HTEAT was accurate within 10 dB of the audiogram PTA in 14% for all ears. The overall accuracy of the HHI to predict normal hearing and hearing loss was 92%.

4 | DISCUSSION

The onset of the COVID-19 pandemic has presented unexpected challenges to healthcare providers, requiring them to adapt quickly to the changing landscape of telehealth and remote care. The evaluation and management of patients with hearing loss particularly has been negatively impacted.[1] Currently, the gold standard for the evaluation of hearing loss is a traditional audiogram, in which a licensed audiologist performs the test in a controlled environment using calibrated equipment. However, rising challenges with healthcare access during the pandemic has pushed providers to develop new strategies for accurate diagnosis and management of these patients. While hearing evaluation applications are widely available, there is a paucity of research assessing the validity of these alternative applications compared to the gold standard.[9] At this point, many providers find it difficult to trust the accuracy and reliability of theses alternative testing methods. To address the lack of data, this study evaluated the correlation between the pure tone averages of audiograms obtained from

commercial (ShoeBox) and consumer (Ear Trumpet & HTEAT) app-based programs as compared to those from a traditional audiogram.

In our study, we found significant strong correlation between the commercial hearing test and traditional audiogram in patients with both normal hearing and hearing loss. In contrast, the consumer apps only had strong correlation with traditional audiogram in patients with hearing loss. When evaluating the accuracy of the apps against traditional audiogram, we observed that the commercial app showed high accuracy while consumer apps had poor accuracy. Furthermore, nearly all participants with normal hearing showed no impairment according to HHI-S, while HHI-S detected hearing impairment in a majority of the hearing loss group. ShoeBox has been explored in pediatric audiology.[13,14] In an ambient environment, ShoeBox was found to have 91.2% sensitivity for hearing loss.[14] Of the consumer apps tested in this study, only EarTrumpet had been previously studied compared to the standard audiometry. This previous study showed that 94% of the threshold values were within 10 dB of the values obtained in standard audiometry when administered in a quiet room.[12] Our study found EarTrumpet was highly correlated to the standard audiogram in patients with hearing loss but were poorly correlated in patients with normal hearing. There were also differences in methods between these studies that may account for this discrepancy (differences in ambient room noise levels, over-ear versus insert headphones, and comparison of individual frequencies versus pure tone averages, potential differences in software versions).

These previous studies demonstrate that both commercial and consumer apps tested align with standard audiometry. Moreover, HHI-S findings largely align with previous studies showing high sensitivity and specificity as well as good test–retest reliability.[15,16]

In past validation studies, comparison of apps to standard audiometry have shown variability due multiple factors including environmental noise, type of transducers, and usability.[9,11] Traditional audiograms are performed in a sound-treated test suite which controls for the environment to ensure quality testing and results. This stands in stark contrast to the consumer and commercial app evaluations which are typically performed at home or in primary care offices with variable ambient noise. To simulate these conditions, this study employed a quiet exam room for the application evaluations. Additionally, the transducer used while participating in these hearing tests may also affect results. ShoeBox includes a calibrated transducer, while HTEAT and Ear Trumpet require user-provided headphones. Previous studies suggest that the type of transducer used (earbud, supra-aural, and circum-aural headphones) largely affect test accuracy based upon the frequency tested and the degree of hearing loss.[17] In consequence, the inclusion of a calibrated headphone with ShoeBox may largely explain the strong correlation with traditional audiometry which uses calibrated equipment.

Although this study highlights the commercial app as a strong potential alternative to the traditional audiometry test, at-home usability is an additional factor to consider. Ideally, an at-home hearing tests need to be easily accessed with clear instructions for self-administration. ShoeBox requires calibrated headphones and significant instruction. While this testing modality may prove useful in offices without access to traditional testing equipment, it would likely prove difficulty for patients to perform at home in a telehealth setting. While not always accurate, the consumer apps still have strong correlation to detect when hearing loss was present without needing extensive calibration and instruction. When considering the telehealth setting, the consumer apps certainly have potential to provide a meaningful and effective means of audiometric evaluation, but certain limitations must be considered with any app-based hearing test. They are severely limited with respect to their ability to determine type and degree of hearing loss. Traditional audiometry can parse out sensorineural versus conductive hearing loss, while app-based hearing tests currently do not. This is an important consideration when treating patients with hearing loss; therefore, app-based hearing tests and the HHI-S may be useful as an initial screening for referral in the context of poor access to traditional testing. Moreover, accessibility to smartphones may be an obstacle in elderly, rural, or lower income populations. Barriers to accessibility is further highlighted in studies looking at the utilization of telehealth during the pandemic, which showed that telehealth made up only 4% of rural healthcare encounters and 7% of urban primary encounters.[2] Mobile hearing healthcare solutions needs to overcome a number of barriers facing mobile technology use among older adults. Based on systematic review, older adult may have difficulty using mobile technology based on a variety of factors including lack of skills in using the interface, cognitive limitations, and mistrust of the technology.[18]

Our study was limited in only evaluating a small set of the hearing test applications available to the public. Recent data published identified 44 unique applications in the Apple App and Google Play stores with only seven apps having validation studies.[11] Our study thus adds to the current literature by evaluating several commercial and consumer apps. By the nature of these applications, there is considerable variability that may result from ambient noise. We designed our study to account for realistic background noise that may be present when these app-based hearing tests are administered in a home or clinic environment. Our study only included 39 participants, studies with larger cohorts could prove effective to validate the use of these alternative applications in various settings. There is still further investigation needed to understand the optimal way these alternative hearing test applications may be integrated in the telehealth setting. Our study supports that these app-based hearing tests do have moderate to strong correlation to traditional audiometry for hearing loss, which may be helpful in screening and evaluating for hearing loss when traditional audiological evaluation is unavailable.

5 | CONCLUSION

While many healthcare providers can provide remote evaluation and management through telemedicine, hearing assessment continues to be a challenge. Alternatives to traditional audiological evaluation, such as the use of smartphone applications may be feasible in providing clinicians a general idea of a patient's audiological status and assist in guiding evaluation and management during times of crisis when a

patient is unable to attend a formal audiological evaluation in person. These applications may provide some useful information regarding configuration, severity, and symmetry of hearing, however, are not intended to replace an evaluation performed in a controlled environment with calibrated equipment and a skillfully trained clinician.

CONFLICT OF INTEREST STATEMENT

MLB is a consultant for Cochlear and Advanced Bionics. There are no conflicts of interests with the content of this manuscript. The authors have no other financial relationships or conflicts of interest to disclose pertaining to the manuscript.

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