J Am Acad Audiol 28:200–208 (2017)

Automated Smartphone Threshold Audiometry: Validity and Time Efficiency

DOI: 10.3766/jaaa.16002

Jessica van Tonder*
De Wet Swanepoel*†‡
Faheema Mahomed-Asmail*
Hermanus Myburgh‡
Robert H. Eikelboom*†‡

Abstract

Background: Smartphone-based threshold audiometry with automated testing has the potential to provide affordable access to audiometry in underserved contexts.

Purpose: To validate the threshold version (hearTest) of the validated hearScreen™ smartphone-based application using inexpensive smartphones (Android operating system) and calibrated supra-aural headphones.

Research Design: A repeated measures within-participant study design was employed to compare air-conduction thresholds (0.5–8 kHz) obtained through automated smartphone audiometry to thresholds obtained through conventional audiometry.

Study Sample: A total of 95 participants were included in the study. Of these, 30 were adults, who had known bilateral hearing losses of varying degrees (mean age = 59 yr, standard deviation [SD] = 21.8; 56.7% female), and 65 were adolescents (mean age = 16.5 yr, SD = 1.2; 70.8% female), of which 61 had normal hearing and the remaining 4 had mild hearing losses.

Data Analysis: Threshold comparisons were made between the two test procedures. The Wilcoxon signed-ranked test was used for comparison of threshold correspondence between manual and smartphone thresholds and the paired samples *t* test was used to compare test time.

Results: Within the adult sample, 94.4% of thresholds obtained through smartphone and conventional audiometry corresponded within 10 dB or less. There was no significant difference between smartphone (6.75-min average, SD = 1.5) and conventional audiometry test duration (6.65-min average, SD = 2.5). Within the adolescent sample, 84.7% of thresholds obtained at 0.5, 2, and 4 kHz with hearTest and conventional audiometry corresponded within ≤5 dB. At 1 kHz, 79.3% of the thresholds differed by ≤10 dB. There was a significant difference ($p < 0.01$) between smartphone (7.09 min, SD = 1.2) and conventional audiometry test duration (3.23 min, SD = 0.6).

Conclusions: The hearTest application with calibrated supra-aural headphones provides a cost-effective option to determine valid air-conduction hearing thresholds.

Key Words: air conduction, automated audiometry, diagnostic audiometry, mHealth, smartphone

Abbreviations: ISO = International Standards Organization; mHealth = mobile health; OS = operating system; SD = standard deviation

*Department of Speech-Language Pathology and Audiology, University of Pretoria, Pretoria, South Africa; †Ear Science Institute Australia, Subiaco, Australia; ‡Ear Sciences Centre, School of Surgery, The University of Western Australia, Nedlands, Australia; §Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria, South Africa

Corresponding author: De Wet Swanepoel, Department of Speech-Language Pathology and Audiology, University of Pretoria, Pretoria, South Africa; E-mail: dewet.swanepoel@up.ac.za

INTRODUCTION

The World Health Organization reports that, globally, 360 million individuals suffer from a disabling hearing loss (WHO, 2013). The vast majority of these individuals have an unidentified hearing loss and reside in low- and middle-income countries (WHO, 2014). Availability of hearing health-care professionals in developing countries is limited (Goulios and Patuzzi, 2008; Windmill and Freeman, 2013) and is unable to meet the demand (Fagan and Jacobs, 2009). It is estimated that there is less than one audiologist for every one million people in developing countries (Fagan and Jacobs, 2009). In addition, the high cost of audiometric equipment and soundproof booths, in combination with a lack of infrastructure and resources, impedes the provision of adequate hearing health-care services (Fagan and Jacobs, 2009; Swanepoel, Olusanya, et al, 2010; Clark and Swanepoel, 2014; Peer and Fagan, 2015).

The increase in innovative technology and global connectivity has resulted in tele-audiology being widely proposed as an affordable and resource-efficient option to combat the lack of skilled hearing health-care professionals and hearing health-care services in some areas (Margolis and Morgan, 2008; Swanepoel, Mngemane, et al, 2010; Swanepoel, Olusanya, et al, 2010; Foulad et al, 2013; Swanepoel et al, 2014). Tele-audiology may be able to bridge the gap between service providers and patients created by geographic and economic barriers (Swanepoel, Olusanya, et al, 2010; Foulad et al, 2013).

The growth in the demand for tele-audiology has led to increased development of audiological software and applications (Mosa et al, 2012; Clark and Swanepoel, 2014). In addition, portable audiometers (Ho et al, 2009; Swanepoel, Clark, et al, 2010; Swanepoel, Olusanya, et al, 2010; Mosa et al, 2012) and smartphone-based hearing tests, such as uHear™ (Unitron, Commack, NY), EarTrumpet (Praxis Biosciences, Irvine, CA), and the Shoebox audiometer (Foulad et al, 2013; Abu-Ghanem et al, 2015; Thompson et al, 2015; Yeung et al, 2015), are allowing provision of hearing health-care services in areas where the absence of soundproof booths and audiological equipment restricts access to care (Ho et al, 2009; Swanepoel, Clark, et al, 2010; Swanepoel, Olusanya, et al, 2010; Mosa et al, 2012; Abu-Ghanem et al, 2015).

Increasing cellular network coverage across the world allows hearing health-care professionals to make use of applications such as videoconferencing and cloud-based data storage to assess and manage patients from more places in the world than ever before (Swanepoel, Clark, et al, 2010; Swanepoel and Biagio, 2011; Mosa et al, 2012; Clark and Swanepoel, 2014). Automated audiometry can be used to conduct screening and full diagnostic audiometry, with results comparable to manual audiometry (Margolis and Morgan, 2008; Swanepoel and Biagio, 2011; Mahomed et al, 2013). Automated diagnostic audiometry effectively reduces the complexity of audiological protocols, allowing for the use of paraprofessionals to facilitate automated hearing assessments (Swanepoel, Mngemane, et al, 2010; Clark and Swanepoel, 2014; Abu-Ghanem et al, 2015). With the option of having paraprofessionals conduct the test battery, hearing health-care professionals may be able to spend more time on patient management, counseling, and intervention (Mosa et al, 2012; Swanepoel et al, 2013). Mobile health (mHealth), as a branch of tele-audiology, is seeing tremendous growth as a means of health promotion and provision because of the widespread penetration of mobile devices throughout developed and developing countries (Kelly and Minges, 2012; Clark and Swanepoel, 2014).

mHealth denotes the use of mobile communication technologies, such as cell phones and tablets, to assist health-care professionals to deliver appropriate services (WHO, 2011). Research indicates that mHealth, in the form of commercially available smartphones, is able to create low-cost solutions for providing hearing health-care services such as screening, assessments, and intervention (Mosa et al, 2012; Swanepoel et al, 2014), even in environments with a lack of resources and poor infrastructure. mHealth enables improved communication between health-care professionals as well as access to assessment tools and patient information (Burdette et al, 2008). In addition, mHealth, in conjunction with emerging technology, allows implementation of quality control during testing by using features such as real-time environmental noise monitoring to ensure results that are comparable to conventional audiometry (Mosa et al, 2012; Swanepoel et al, 2014; Mahomed-Asmail et al, 2015). As such, smartphones could enable health-care professionals to provide efficient and effective services to their patients (Burdette et al, 2008).

To date, several smartphone applications have been developed to test hearing (Foulad et al, 2013; Swanepoel et al, 2014; Abu-Ghanem et al, 2015; Thompson et al, 2015; Yeung et al, 2015). For example, uHear™, a smartphone-based application for Apple iOS (Apple Inc, Cupertino, CA), is a self-administered air-conduction threshold test (Peer and Fagan, 2015). Several studies have been conducted to compare uHear™ to conventional audiometry and have yielded mixed outcomes. In a study conducted by Peer and Fagan (2015), uHear™ was able to accurately identify disabling hearing loss as well as detect early high-frequency threshold changes. In a study conducted by Szudek et al (2012), uHear™ was able to accurately rule out a moderate hearing loss as well as determine the degree of hearing loss in individuals with hearing loss. However, in this study, uHear™ was found to overestimate the hearing thresholds of normal-hearing individuals (Szudek et al, 2012). As a result, normal-hearing individuals often presented with hearing loss (Szudek et al, 2012). Similarly, in a study conducted

by Khoza-Shangase and Kassner (2013), uHear™ produced elevated thresholds when compared to thresholds obtained through manual audiometry. In contrast to uHear™, the EarTrumpet, which is also a self-administered Apple iOS smartphone application, yields results that are comparable to conventional audiometry (Foulad et al, 2013). The mixed outcomes of Apple iOS application studies could be attributed to limitations, such as the lack of calibrated headphones that adhere to calibration standards (e.g., International Standards Organization [ISO] and ANSI). Some applications, such as Shoebox audiometry, have attempted to solve this problem by coupling audiometric headphones to the Apple iPad (Yeung et al, 2013). The Shoebox audiometer is a self-administered, automated, air-conduction threshold test that is able to determine hearing thresholds between 15 and 90 dB HL that are comparable to conventional audiometry (Yeung et al, 2013; Thompson et al, 2015). This solution may be prohibitively costly in developing countries, considering that many Apple iOS devices are high-end products with poor penetration in developing world regions (Kochi, 2012), with applications that can be purchased only through the Apple App Store (Kelly and Minges, 2012).

A low-cost smartphone application, using Android operating system (OS; Google Inc, Santa Clara, CA) smartphones, has also been reported for hearing testing (Swanepoel et al, 2014). The hearScreen™ application has provided the first inexpensive Android smartphone solution coupled with calibrated headphones (Swanepoel et al, 2014). hearScreen™ is able to accurately screen hearing on a "pass/fail" criterion (Mahomed-Asmail et al, 2015). Extending the hearScreen™ application for automated threshold audiometry could increase the reach of cost-effective hearing testing, through smartphones operated by trained laypersons or paraprofessionals in primary health-care settings. The current study investigated the validity of a threshold version of the validated hearScreen™ smartphone-based application (hearTest), using inexpensive smartphones (Android OS) and calibrated supra-aural headphones.

The purpose of this study was to determine the concurrent validity of the smartphone application when compared to conventional audiometry. Concurrent validity is used when a new test method is proposed as a substitute for the gold standard method (Chin and Lee, 2008). This validation technique requires both methods to be evaluated at the same time to determine the correlation between them (Chin and Lee, 2008).

METHOD

Approval to include human participants to conduct this study was granted by the appropriate institutional review board before data collection commenced. Adults and adolescents with hearing sensitivity ranging from normal to profound were chosen as participants to obtain results for a wide range of hearing sensitivity. Participants for the adult sample were patients recruited from two audiological clinics at a South African university, the hearing assessment and hearing aid fitting clinic, and a private audiology practice in the West Rand of Johannesburg, South Africa. Participants for the adolescent sample were recruited from a prospective students' program at the abovementioned university. All participants provided written informed consent. In instances where the participants were aged <18 yr, written consent was obtained from the parents, as legal guardians of the participants, as well as written assent from each participant before data collection.

Participants

There were 95 participants included in the study: 30 adults and 65 adolescents. For the adult participants, ages ranged between 24 and 92 yrs. The mean age was 59 yr (standard deviation [SD] = 21.8 yr), of which 56.7% were female. Adult participants were evaluated by means of a full diagnostic test battery, in the respective clinics, to determine the type, magnitude, and configuration of their hearing loss. However, for the purpose of this study, only the results of the air-conduction thresholds were used for comparison with the smartphone application. All adult participants presented with sensorineural hearing losses ranging from mild to profound, as classified by ASHA (2011).

For the adolescent participants, ages ranged between 16 and 21 yrs. The mean age was 16.5 yr (SD = 1.2 yr), and 70.8% of the participants were female. The majority (n = 61) had normal-hearing sensitivity, with a pure-tone average ≤20 dB HL. The remaining four participants had mild hearing losses, with a pure-tone average between 21 and 40 dB HL, which were identified using air- and bone-conduction audiometry. However, for the purpose of this study, only the results of the air-conduction thresholds were used for comparison with the smartphone application.

Equipment

Two methods of air-conduction threshold estimation were conducted: conventional air-conduction audiometry and automated smartphone-based air-conduction audiometry using hearTest.

Conventional Audiometry

When conventional audiometry was administered, one of two audiometers was used. Participants obtained from the university were tested with the GSI 61 two-channel audiometer (Grason-Stadler Inc, Eden Prairie, MN) coupled with TDH 39 audiometric headphones

(Telephonics Corp., Farmingdale, NY). Participants at the private audiological practice were tested with the GN Otometrics Otosuite (GN Otometrics, Taastrup, Denmark) loaded onto a Lenovo (Morrisville, NC) z50 Notebook couple with 10-ohm Otometrics insert earphones (GN Otometrics). In both instances, participants were tested by either a qualified audiologist (author J.v.T.) or a final-year audiology student of the university under the supervision of a qualified audiologist. Testing was conducted in an ISO 6189 (1983) compliant soundproof booth and all apparatus was calibrated to meet the current ISO 389-1 (1998) and 389-2 (1994) standards.

Automated Smartphone Audiometry

In the case of automated diagnostic audiometry, the hearTest application was loaded onto a Samsung SM-G313H Trend Neo Smartphone (Samsung, Suwon, South Korea) and run by Android OS version 4.4 coupled with Sennheiser HD 202 II supra-aural headphones (Wedemark, Germany). The hearTest application is a smartphone-based, self-administered, automated hearing assessment. The hearScreen™ calibration function (Swanepoel et al, 2014) was used to calibrate the Sennheiser HD 202 II headphones according to prescribed standards (ISO, 1998) adhering to equivalent threshold sound pressure levels determined for this headphone (Van der Aerschot et al, 2016) according to ISO 389-9 (2009). Calibration was performed using an IEC 60318-1 G.R.A.S. ear stimulator (G.R.A.S Sound & Vibration, Holte, Denmark) connected to a Type 1 SLM (Rion NL-52; Rion Science & Technology Shanghai LTD, Shanghai, China). Testing was conducted in an ISO 6189 (1983) compliant soundproof booth.

The absolute maximum intensity differed across frequencies according to the output capability of the Sennheiser HD 202 II headphones. From 0.5 to 4 kHz, the intensity limit was 90 dB HL, and at 8 kHz the intensity limit was 80 dB HL. The hearTest output level was restricted to 10 dB HL. Therefore, hearing thresholds below 10 dB HL at 0.5–8kHz were not established to account for the minimum output level of hearTest.

Procedures

A repeated measures within-participant study design (Leedy and Ormrod, 2014) was employed to compare smartphone audiometry to conventional audiometry. As such, each participant underwent testing for both threshold-seeking methods. Counterbalancing methods were employed, in the adult sample, to reduce the likelihood of test order adversely affecting test outcomes. Therefore, test order started with conventional audiometry in 53% of cases for the adult sample. However, participants in the adolescent sample were sourced from a busy hearing screening clinic. Because of strict time constraints, and the numbers of individuals who needed to be screened, counterbalancing could not be enforced. As a result, test order started with conventional audiometry in 34% of the cases. Blinding procedures were employed for both samples. Audiologists conducting the second threshold determination method were blind to results of the first test.

Conventional audiometry threshold determination commenced in the best ear as reported by the participant. Test frequencies included 0.5, 1, 2, 4, and 8 kHz. Hearing thresholds were determined using the ISO shortened ascending method (ISO, 2010). Threshold determination started at 40 dB HL at 1 kHz, followed by 0.5 kHz and then 2–8 kHz. Participants were instructed to press a handheld response button every time a tone was heard. Thresholds <10 dB HL were not determined, due to the minimum output level of the hearTest. Test duration was timed using a stopwatch.

The automated self-administered smartphone testing determined thresholds across the frequencies 0.5, 1, 2, 4, and 8 kHz. An automatic test protocol using

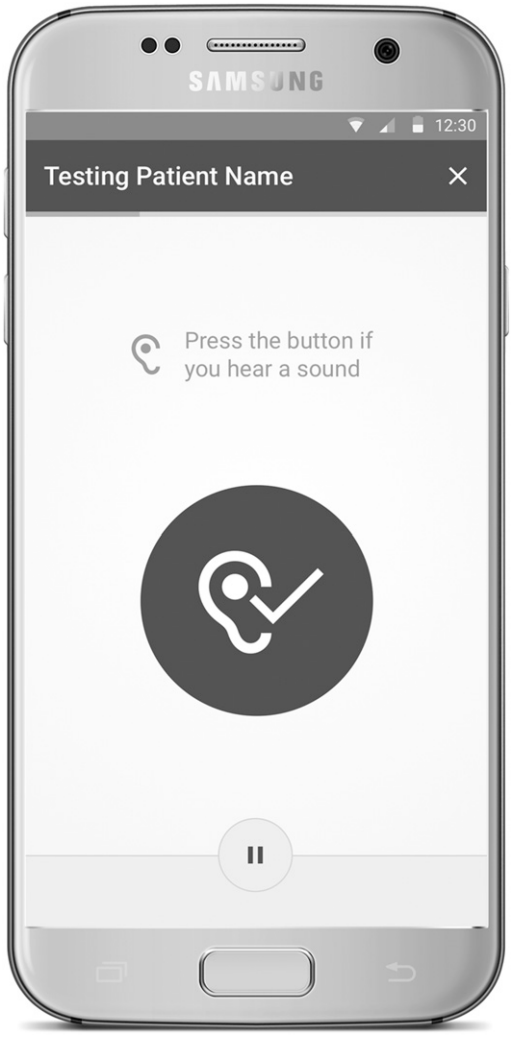

Figure 1. hearTest response button.

the ISO shortened ascending method (ISO, 2010) was implemented. Participants were instructed to touch a response button on the smartphone screen every time a tone was heard (Figure 1). In the event that the participant touched the response button (positive response) the tone was automatically decreased by 10 dB. In the event that the participant did not push the response button (negative response) the tone was automatically increased by 5 dB. A positive response was recorded as a threshold when two of three responses occurred at the same level with three ascents. A negative response was recorded when the maximum intensity was reached without a response from the participant. A blinding procedure was employed for both samples. In the adult sample, conventional audiometry was conducted by the university's students under the supervision of a qualified audiologist, or by a second qualified audiologist. In the adolescent sample, conventional audiometry was conducted by a third qualified audiologist. In both samples, the smartphone threshold test was facilitated by author J.v.T. Test duration was recorded by the application during the test procedure. Once the test procedure was complete, the test administrator uploaded the test results to the hearData server. The administrator was then able to access the cloud-based server to review the test results.

Analysis

Results were analyzed to account for the possible influence of a floor effect because testing was conducted only down to 10 dB HL. A comparative analysis between thresholds (conventional versus smartphone audiometry) was done where thresholds of 10 dB HL in either test condition were excluded. Within the adult sample, there were 17 instances, out of a possible 300 instances, where responses could not be obtained at the maximum intensities on the hearTest but were obtained at higher intensities through conventional audiometry. In those instances, comparisons could not be made. Threshold data for conventional audiometry and smartphone audiometry (>10 dB HL) were analyzed descriptively for average differences, average absolute differences, and respective distributions. Corresponding thresholds between conventional and smartphone audiometry were determined and expressed as a percentage of cases within 5 dB, within 10 dB, and differing by 15 dB or more. Correspondence between conventional and smartphone test duration was determined.

Statistical analyses were performed using SPSS (SPSS Inc., Chicago, IL) and Microsoft Excel (Microsoft Inc., Redmond, WA). The data were not normally distributed (Shapiro–Wilk test of normality), necessitating nonparametric analyses (Wilcoxon signed-rank tests) to determine if there were significant differences between conventional audiometry and smartphone testing ($p < 0.01$).

RESULTS

Smartphone Threshold Accuracy and Test Duration in Adults

There was no statistically significant difference between smartphone and conventional thresholds in the adult sample across all frequencies except at 4 kHz ($p > 0.01$). The majority (70.6%) of thresholds obtained through smartphone and conventional audiometry differed by ≤5 dB (Table 1). Further analysis was conducted on the floor scores, which showed that 90.5% of the thresholds obtained within the adult sample were not affected by the floor effect in either condition (Table 2).

Mean test durations for hearTest (6.75-min average, SD = 1.5) and conventional audiometry (6.65-min average, SD = 2.5) were not significantly different ($p > 0.01$; Wilcoxon).

Smartphone Threshold Accuracy and Test Duration in Adolescents

The majority (84.7%) of thresholds obtained at 0.5, 2, and 4 kHz with hearTest and conventional audiometry differed by ≤5 dB and at 1 kHz, the majority (79.3%) of the thresholds differed by ≤10 dB (Table 3). Although a statistically significant difference between smartphone and conventional thresholds in the adolescent sample across all frequencies except at 8 kHz ($p < 0.01$) was noted, it may not be clinically significant; 90.8% of the threshold comparisons were affected by the floor effect (Table 3).

Table 1. Average Difference* and Correspondence between Smartphone and Conventional Audiometry per Frequency for the Adult Population (n = 30)

		Frequency (kHz)				
		0.5	1	2	4	8
Threshold comparisons (n)		58	59	57	52	42
Average difference (dB)	Mean	1.9	0	1.0	−3.1**	−0.1
	SD	6.4	6.8	6.7	6.4	6.8
Correspondence (%)	0–5 dB	69	67.8	78.9	63.5	73.9
	±10 dB	25.9	28.8	10.6	34.6	19
	≥15 dB	5.1	3.4	10.5	1.9	7.1
Threshold comparisons excluding floor effect (n)		49	49	51	49	41
Average difference (dB)	Mean	2.9	1.2	1.6	−3.3**	0
	SD	6.7	6.6	6.6	6.2	6.8
Correspondence (%)	0–5 dB	67.3	71.4	80.5	65.3	73.2
	±10 dB	26.5	24.5	7.8	32.7	19.5
	≥15 dB	6.2	4.1	11.7	2	7.3

Notes: *hearTest subtracted from conventional audiometry thresholds.

**Significant difference ($p < 0.01$).

Table 2. Distribution of Thresholds for Manual and Smartphone Audiometry in Adolescent Sample (n = 130 Ears)

Threshold Category		Frequency (kHz)				
		0.5	1	2	4	8
1	hearTest and conventional = 10 dB (%)	6.2	6.2	6.2	72.3	82.3
2	hearTest >10 dB and conventional = 10 dB (%)	85.4	83.8	83.1	19.2	3.1
3	hearTest = 10 dB and conventional >10 dB (%)	0	0	0	0	6.2
4	hearTest >10 dB and conventional >10 dB (%)	8.5	10	10.8	8.5	8.5

Mean test durations for hearTest (7.09 min, SD = 1.2) and conventional audiometry (3.23 min, SD = 0.6) differed significantly ($p > 0.01$; Wilcoxon) with a difference of 3.86 min between the mean times of the two methods.

Absolute average differences for the adult and adolescent samples combined (Table 4), excluding the floor effect, varied between 4.6 (SD = 4.5) and 5.9 dB (SD = 4.3).

DISCUSSION

Validating a new method of pure-tone threshold audiometry requires comparisons against conventional manual pure-tone audiometry (Mahomed et al, 2013). The current study demonstrated that hearing thresholds obtained with the hearTest smartphone application are within clinically acceptable ranges compared to conventional audiometry thresholds. Recent studies comparing mean threshold differences between conventional audiometry and automated audiometry are in agreement with the findings of the current study, yielding results that are comparable to conventional audiometry within individuals with hearing impairment (Swanepoel and Biagio, 2011; Eikelboom et al, 2013; Mahomed et al, 2013; Mahomed-Asmail et al, 2016). A comparison of the thresholds obtained through conventional and automated audiometry in this study produced threshold differences ranging between −3.3 (SD = 6.2) and 2.9 dB (SD = 6.7) for the adult sample and between −3.2 (SD = 4.2) and 2.3 (SD = 3.5) for the adolescent sample. These results are lower than threshold differences reported by Swanepoel and Biagio (2011), but are in line with a meta-analysis, on the validity of automated compared to manual threshold audiometry, conducted by Mahomed et al (2013) as well as results obtained in studies conducted by Eikelboom et al (2013) and Mahomed-Asmail et al (2016). Absolute average threshold differences (excluding any floor effect) for the adult and adolescent samples (Table 4) show variability (SDs) of between 4.3 and 4.6 dB across frequencies. This is comparable to typical test–retest variability (SDs) of between 3.4 and 4.1 dB as reported in a meta-analysis of manual audiometry (Mahomed et al 2013).

To date, several studies comparing smartphone and conventional audiometry have been conducted, with varied results. In some instances, automated smartphone audiometry has been found to overestimate hearing thresholds (Khoza-Shangase and Kassner, 2013; Abu-Ghanem et al, 2015). In these instances, smartphone applications seem better suited as simple end-user screening tools not intended for clinical application (Abu-Ghanem et al, 2015). In contrast, some studies have found smartphone applications to produce hearing thresholds that are comparable to conventional audiometry (Foulad et al 2013; Thompson et al, 2015). Thompson et al (2015) used the iOS Shoebox tablet audiometer to obtain hearing thresholds and concluded that automated audiometry could be used to accurately determine hearing thresholds in a study sample of 44 adults and 5 children. Foulad et al (2013) used the iOS EarTrumpet smartphone application and determined that smartphone audiometry is able to obtain hearing thresholds comparable to conventional audiometry without the use of additional equipment. The current study results, within the adolescent sample, agree with Thompson et al (2015) and Foulad et al (2013) with findings demonstrating thresholds equivalent to conventional pure-tone audiometry. The current study, however, is the first

Table 3. Average Difference* and Correspondence between hearTest and Conventional Audiometry per Frequency for the Adolescent Population (n = 65)

		Frequency (kHz)				
		0.5**	1**	2**	4**	8
Number of threshold comparisons (n)		130	130	130	130	130
Average difference (dB)	Mean	−4.4	−8.4	−6.6	−1.2	0
	SD	2.9	4.3	3.5	2.9	3.1
Correspondence (%)	0–5 dB	92.3	17.6	57.7	95.4	93.1
	±10 dB	7.7	79.3	40.8	4.6	6.1
	≥15 dB	0	3.1	1.5	0	0.8
Threshold comparisons excluding floor effect (n)		11	13	14	11	11
Average difference (dB)	Mean	2.3	1.2	−3.2	−1.4	−2.7
	SD	3.5	8	4.2	5.5	5.6
Correspondence (%)	0–5 dB	90.9	69.2	85.7	81.8	81.8
	±10 dB	9.1	15.5	14.3	18.2	9.1
	≥15 dB	0	15.3	0	0	9.1

Notes: *hearTest subtracted from conventional audiometry thresholds.

**Significant difference ($p < 0.01$).

Table 4. Average Absolute Difference for Thresholds Unaffected by a Floor Effect in the Adult and Adolescent Samples

	Frequency (kHz)				
	0.5	1	2	4	8
Number	60	62	65	60	52
Absolute average difference	5.9	5.2	4.6	5.4	4.6
SD	4.3	4.5	4.5	3.9	4.7

to use inexpensive Android smartphones and calibrated headphones.

Hearing threshold variation, of 10 dB or less, between two methods of hearing assessment is accepted as subclinical within the context of clinical diagnostic audiometry (OSHA, 1983; McDaniel et al, 2013). It should be noted that, in some instances, for example with children, a difference of 10 dB HL could potentially be significant. In the current study, with the same standard adopted during data analysis, 94.4% of the adult sample thresholds obtained, using the smartphone, were within 10 dB of the thresholds obtained using conventional audiometry. Similarly, 98% of the adolescent sample thresholds were within 10 dB. These findings are consistent with those of several similar studies using iOS and Android OS devices (Mahomed et al, 2013; Yeung et al, 2013; Thompson et al, 2015).

There was no significant difference in test duration within the adult sample. These findings are in agreement with those of Abu-Ghanem et al (2015), using uHear™. However, there was a significant difference in test duration within the adolescent sample. Conventional audiometry testing took 3.23 min (SD = 0.6); these findings are in line with the study conducted by Mahomed-Asmail et al (2016), which reported conventional audiometry test duration at 3.63 min (SD = 2.17). The brief test duration could be attributed to the majority of these participants having normal hearing with most thresholds below 15 dB. Due to the hearTest's minimum test level of 10dB, the majority of thresholds were, in fact, minimum response levels at 10 dB HL. Furthermore, findings indicated that smartphone testing took 3.86 min longer than conventional audiometry. The discrepancy in test duration within the adolescent sample is likely related to the standardized automated threshold method taking longer than conventional audiometry to test down to normal levels (15 dB HL and lower). The application was set with standard "waiting periods" between responses and presentation of the next intensity and/or frequency. This is, however, not a concern when using conventional audiometry, seeing as the speed of the test is largely based on the participant's response time. Furthermore, the smartphone application requires a loading period of one to two seconds to store the threshold information at the end of each frequency's test and move on to the next frequency. This loading period is not necessary when using conventional audiometry. However, the exact cause remains unknown and requires further investigation.

The hearTest application shares several key features with hearScreen™, such as integrated real-time noise monitoring, instant data capturing, and cloud-based data storage. Automated test paradigms, along with these quality control features, allow laypersons with limited training to facilitate hearing assessments (Swanepoel et al, 2014; Yousuf Hussein et al, 2015; Mahomed-Asmail et al, 2016). This type of technology can ensure hearing health-care professionals spend more time on patient management and intervention (Swanepoel et al, 2013; Clark and Swanepoel, 2014).

In developing countries, where the lack of appropriate hearing health-care professionals and infrastructure is common (Fagan and Jacobs, 2009), the mobility of audiological equipment, with quality control features, allows for wider penetration of hearing health services (Clark and Swanepoel, 2014; Peer and Fagan, 2015). This would specifically benefit communities with residents who are treated with ototoxic medication for conditions such as tuberculosis, human immunodeficiency virus, and cancer as well as accompanying opportunistic infections (Harris et al, 2012). It is recommended that these individuals undergo evaluations to monitor audiological status as often as twice a week (Duggal and Sarkar, 2007), and it is therefore essential that these individuals have access to hearing health-care services that are readily available and easily accessible. Furthermore, these services could be initiated in community health and satellite clinics or could be taken directly to at-risk patients in their homes, to make hearing health-care services even more accessible (Fagan and Jacobs, 2009; Clark and Swanepoel, 2014; Peer and Fagan, 2015).

A limitation of this study was the influence of the floor effect, created by testing only down to 10 dB HL. However, when considering the impact of the floor effect it should be noted that threshold levels of ≤15 dB HL are typically taken as normal for children. While the impact of the floor effect could be a limitation in sound-treated environments, smartphone testing is primarily intended for community or primary health-care access where testing below 10 dB would be difficult if not impossible due to ambient noise. Therefore, it is recommended that future research be conducted to determine the ability of the hearTest to accurately test down to 0 dB HL. In addition, the lack of bone-conduction testing results in the inability of the hearTest to determine the type of loss in hearing-impaired individuals. Furthermore, all testing was conducted in a soundproof booth. It is recommended that smartphone testing be evaluated outside of the booth, employing the noise-monitoring quality control features to evaluate to validity of testing outside sound-treated environments. Reliable results outside of a soundproof booth could allow for a substantial reduction in the costs

involved with purchasing hearing health-care equipment. As a result, hearing health-care services will be more readily available and easily accessible to individuals living in both developed and developing countries.

Currently, the hearTest application lays important groundwork for the development of a cost-effective, commercially available, and portable hearing assessment device. Future studies evaluating the effectiveness of the hearTest's air-conduction threshold determination, in conjunction with bone conduction and masking, as well as the application's added features of real-time noise monitoring and data management capabilities, could give hearing health-care professionals in underserved areas the ability to successfully assess and manage the hearing-impaired population, potentially resulting in the disabling effects of hearing impairment across the continent being significantly reduced.

CONCLUSION

The hearTest smartphone application for threshold audiometry provides hearing thresholds comparable to conventional manual air-conduction audiometry. While the hearTest smartphone application does not allow for differential diagnoses, because it does not include bone-conduction audiometry, it can be used as a threshold baseline and monitoring tool. Use of smartphone-based audiometry may provide a time-efficient, cost-effective, and portable solution, allowing for hearing service provision in remote and underserved areas (Swanepoel, Clark, et al, 2010; Foulad et al, 2013; Swanepoel et al, 2014).

REFERENCES

Abu-Ghanem S, Handzel O, Ness L, Ben-Artzi-Blima M, Fait-Ghelbendorf K, Himmelfarb M. (2015) Smartphone-based audiometric test for screening hearing loss in the elderly. *Eur Arch Otorhinolaryngol* 273(2):333–339.

American Speech-Language-Hearing Association (ASHA). (2011) Type, degree and configuration of hearing loss. http://www.asha.org/uploadedFiles/AIS-Hearing-Loss-Types-Degree-Configuration.pdf. Accessed June 8, 2015.

Burdette SD, Herchline TE, Oehler R. (2008) Surfing the web: practicing medicine in a technological age: using smartphones in clinical practice. *Clin Infect Dis* 47(1):117–122.

Chin R, Lee B. (2008) *Principles and Practice of Clinical Trial Medicine*. London, UK: Elsevier Inc.

Clark JL, Swanepoel W. (2014) Technology for hearing loss—as We Know it, and as We Dream it. *Disabil Rehabil Assist Technol* 9(5):408–413.

Duggal P, Sarkar M. (2007) Audiologic monitoring of multi-drug resistant tuberculosis patients on aminoglycoside treatment with long term follow-up. *BMC Ear Nose Throat Disord* 7(5):5.

Eikelboom RH, Swanepoel DW, Motakef S, Upson GS. (2013) Clinical validation of the AMTAS automated audiometer. *Int J Audiol* 52(5):342–349.

Fagan JJ, Jacobs M. (2009) Survey of ENT services in Africa: need for a comprehensive intervention. *Glob Health Action* 2:1–7.

Foulad A, Bui P, Djalilian H. (2013) Automated audiometry using Apple iOS-based application technology. Otolaryngol *Head Neck Surg* 149(5):700–6.

Goulios H, Patuzzi RB. (2008) Audiology education and practice from an international perspective. *Int J Audiol* 47(10): 647–664.

Harris T, Peer S, Fagan J. (2012) Audiological monitorig for ototoxic tuberculosis, human immunodeficiency virus and cancer therapies in a developing world setting. *J Laryngol Oto* 126: 548–551.

Ho A, Hildreth A, Lindsey L. (2009) Computer-assisted audiometry versus manual audiometry. *Otol Neurotol* 30:876–883.

International Standards Organization (ISO). (1983) *Acoustics—Pure Tone Air Conduction Threshold Audiometry for Hearing Conservation Purposes* (ISO 6189:1983).

International Standards Organization (ISO). (1994) *Acoustics—Reference Zero for the Calibration of Audiometric Equipment—Part 2: Reference Equivalent Threshold Sound Pressure Levels for Pure Tones and Insert Earphones* (ISO 389-2:1994).

International Standards Organization (ISO). (1998) *Acoustics—Reference Zero for the Calibration of Audiometric Equipment—Part 1: Reference Equivalent Thresholds Sound Pressure Levels for Pure Tones and Circumaural Earphones* (ISO 389-1: 1998).

International Standards Organization (ISO). (2009) *Acoustics—Reference Zero for the Calibration of Audiometric Equipment—Part 9: Preferred Test Conditions for the Determination of Reference Hearing Threshold Levels* (ISO 389-9:2009).

International Standards Organization (ISO). (2010) *Acoustics—Audiometric Test Methods—Part 1: Pure Tone Air and Bone Conduction Audiometry* (ISO 8253-1:2010).

Kelly T, Minges M. (2012) *Exclusive Summary*. Washington, DC: World Bank.

Khoza-Shangase K, Kassner L. (2013) Automated screening audiometry in the digital age: exploring uHear™ and its use in a resource-stricken developing country. *Int J Technol Assess Health Care* 29(1):42–47.

Kochi E. (2012) How the future of mobile lies in the developing world. http://techcrunch.com/2012/05/27/mobile-developing-world/. Accessed February 27, 2016.

Leedy P, Ormrod J. (2014) *Practical Research: Planning and Design*. 10th ed. Essex, UK: Pearson Education Limited.

Mahomed F, Swanepoel D, Eikelboom RH, Soer M. (2013) Validity of automated threshold audiometry: a systematic review and meta-analysis. *Ear Hear* 34(6):745–752.

Mahomed-Asmail F, Swanepoel D, Eikelboom RH. (2016) Diagnostic hearing assessment in schools: validity and time-efficiency of automated audiometry. *J Am Acad Audiol* 27(1):42–48.

Mahomed-Asmail F, Swanepoel D, Eikelboom R, Myburgh H, Hall J. (2015) Clinical validity of hearScreen smartphone: hearing screening for school children. *Ear Hear* 37(1):e11–e17.

Margolis RH, Morgan DE. (2008) Automated pure-tone audiometry: an analysis of capacity, need, and benefit. *Am J Audiol* 17(2): 109–113.

McDaniel M, Chinn G, McCall K, Stewart A. (2013) Guidelines for audiometric baseline revision. http://c.ymcdn.com/sites/www.hearingconservation.org/resource/resmgr/Position_Statements/Guidelines_for_Audiometric_B.pdf. Accessed February 27, 2016.

Mosa AS, Yoo I, Sheets L. (2012) A systematic review of healthcare applications for smartphones. *BMC Med Inform Decis Mak* 12:67–98.

Occupational Saftey and Health Administration (OSHA). (1983) Occupational noise exposure; hearing conservation amendment. *Fed Regist* 48:9738–9785.

Peer S, Fagan JJ. (2015) Hearing loss in the developing world: evaluating the iPhone mobile device as a screening tool. *S Afr Med J* 105(1):35–39.

Swanepoel D, Biagio L. (2011) Validity of diagnostic computer-based air and forehead bone conduction audiometry. *J Occup Environ Hyg* 8(4):210–214.

Swanepoel D, Clark JL, Koekemoer D, Hall JW 3rd, Krumm M, Ferrari DV, McPherson B, Olusanya BO, Mars M, Russo I, Barajas JJ. (2010) Telehealth in audiology: the need and potential to reach underserved communities. *Int J Audiol* 49(3):195–202.

Swanepoel D, Maclennan-Smith F, Hall J. (2013) Diagnostic puretone audiometry in schools: Mobile testing without a sound-treated evironment. *J Am Acad Audiol* 24:992–1000.

Swanepoel D, Mngemane S, Molemong S, Mkwanazi H, Tutshini S. (2010) Hearing assessment—reliability, accuracy, and efficiency of automated audiometry. *Telemed J E Health* 16(5): 557–563.

Swanepoel D, Myburgh H, Howe D, Mahomed F, Eikelboom R. (2014) Smartphone hearing screening with integrated quality control and data management. *Int J Audiol* 53(12):841–9.

Swanepoel D, Olusanya BO, Mars M. (2010) Hearing health-care delivery in sub-Saharan Africa—a role for tele-audiology. *J Telemed Telecare* 16(2):53–56.

Szudek J, Ostevik A, Dziegielewski P, Robinson-Anagor J, Gomaa N, Hodgetts B, Ho A. (2012) Can Uhear me now? Validation of an iPod-based hearing loss screening test. J Otolaryngol *Head Neck Surg* 41:78–84.

Thompson G, Sladen D, Borst BJ, Still O. (2015) Accuracy of a tablet audiometer for measuring behavioural hearing thresholds in a clinical population. Otolaryngology *Head Neck Surg* 153(5): 838–842.

Van der Aerschot M, Swanepoel D, Mahomed-Asmail F, Myburgh HC, Eikelboom RH. (2016) Affordable headphones for accessible screening audiometry: an evaluation of the Sennheiser HD202 II supra-aural headphone. *Int J Audiol* [in press].

Windmill IM, Freeman BA. (2013) Demand for audiology services: 30-yr projections and impact on academic programs. *J Am Acad Audiol* 24(5):407–416.

World Health Organisation (WHO). (2011) *mHealth: New Horizons for Health through Mobile Technologies: Second Global Survey on eHealth*. Geneva, Switzerland: World Health Organisation.

World Health Organisation (WHO). (2013) *Multi-Country Assessment of National Capacity to Provide Hearing Care*. Geneva, Switzerland: World Health Organisation.

World Health Organisation (WHO). (2014) Fact sheet 300: Deafness and hearing impairment. http://0-www.who.int.innopac.up.ac.za/mediacentre/factsheets/fs300/en/. Accessed June 8, 2015.

Yeung J, Javidnia H, Heley S, Beauregard Y, Champagne S, Bromwich M. (2013) The new age of play audiometry: prospective validation testing of an iPad-based play audiometer. *J Otolaryngol Head Neck Surg* 42:21.

Yeung JC, Heley S, Beauregard Y, Champagne S, Bromwich MA. (2015) Self-administered hearing loss screening using an interactive, tablet play audiometer with ear bud headphones. *Int J Pediatr Otorhinolaryngol* 79(8):1248–1252.

Yousuf Hussein S, Swanepoel W, Biagio de Jager L, Myburgh HC, Eikelboom RH, Hugo J. (2015) Smartphone hearing screening in mHealth assisted community-based primary care. *J Telemed Telecare*: [early online edition] 1–8.