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Monitoring Hearing in an Infectious Disease Clinic with mHealth Technologies

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Abstract

Background: Decentralized detection and monitoring of hearing loss can be supported by new mobile health technologies using automated testing that can be facilitated by minimally trained persons. These may prove particularly useful in an infectious disease (ID) clinic setting where the risk of hearing loss is high.

Purpose: To evaluate the clinical utility of mobile and automated audiometry hearing health technology in an ID clinic setting.

Research Design: Smartphone-automated pure-tone audiometry (PTA) (hearTest™) and speech-in-noise testing (SA English digits-in-noise [DIN] test) were compared with manual audiometry (2, 4, and 8 kHz). Smartphone-automated PTA and the DIN test were repeated to determine the test–retest reliability.

Study Sample: Two hundred subjects (73% female and 27% male) were enrolled. Fifty participants were retested with the smartphone applications. Participants ranged from an age of 18 to 55 years with a mean age of 44.4 (8.7 standard deviation).

Data Analysis: Threshold comparisons were made between smartphone audiometry testing and manual audiometry. Smartphone-automated PTA, manual audiometry, and test–retest measures were compared (Wilcoxon signed ranked test). Spearman rank correlation test was used to determine the relationship between the smartphone applications and manual audiometry, as well as for test–retest reliability.

Results: Within all participants, 88.2% of thresholds corresponded within 10 dB or less between smartphone audiometry and manual audiometry. There was a significant difference ($p < 0.05$) between the right ear at 4 and 8 kHz and in the left ear at 2 and 4 kHz between smartphone and manual audiometry, respectively. No significant difference was noted ($p < 0.05$) between test and retest measures of smartphone technology.

Conclusions: Smartphone audiometry with calibrated headphones provides reliable results in an ID clinic setting and can be used as a baseline and monitoring tool at ID clinics.

Key Words: audiometry, hearing loss, human immunodeficiency virus, mobile health

Abbreviations: AIDS = acquired immune deficiency syndrome; ARV = antiretroviral therapies; DIN = digits in noise; HIV = human immunodeficiency virus; ID = infectious disease; ISO = international standards organization; mHealth = mobile health; PTA = pure-tone audiometry; SD = standard deviation; SNR = signal-to-noise ratio; TB = tuberculosis

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The hearTest™ application is intellectual property owned and trademarked by the University of Pretoria. The third author has a relationship with the hearX Group, who owns the right to the IP that includes equity, consulting, and potential royalties.

INTRODUCTION

Hearing loss is closely associated with various infectious diseases (IDs) due to intrinsic causes related to the infection and extrinsic causes related to the medications (Cohen et al, 2014). Human immunodeficiency virus (HIV), acquired immune deficiency syndrome (AIDS), and tuberculosis (TB) are examples of IDs.

The use of antiretroviral therapies (ARVs) has improved life expectancy (Jolles et al, 1996), which shifted the paradigm of HIV/AIDS from life-threatening to the quality of life (Eloff, 2010). With increased life expectancy, individuals with HIV/AIDS are now at a higher risk for developing comorbid diseases (Marin et al, 2009; Peters et al, 2013). Head and neck diseases are of the first to arise, such as manifestations of the ear that result in auditory and otologic symptoms (Bankaitis and Keith, 1995; Khoza-Shangase and Ross, 2002; van der Westhuizen et al, 2013; Matas et al, 2014). Symptoms can include otorrhea, tinnitus, otalgia, and hearing loss (Khoza-Shangase and Ross, 2002; Prasad et al, 2006). Hearing loss can develop because of the direct effect of the virus on the auditory nerve, through opportunistic infections or ototoxicity (Chandrasekhar et al, 2000; Stearn and Swanepoel, 2010). Ototoxicity can be a result of combinations of ARVs and the effect of medications prescribed for opportunistic infection (Bankaitis and Schountz, 1998), and among opportunistic infections, TB has the highest prevalence among HIV patients (WHO, 2016). Aminoglycosides are core ingredients for TB medication but also are considered toxic, and can potentially cause an irreversible hearing loss (Modongo et al, 2014).

Hearing loss can decrease one's quality of life by the inability to function independently and to contribute to society in daily living (Olusanya et al, 2006; Chia et al, 2007; Gopinath et al, 2012; Mick et al, 2014). From early 1985, numerous studies have reported otological manifestations related to HIV/AIDS with a sensorineural hearing loss present in this population that range from 14% (Khoza-Shangase and Ross, 2002) to 76% (Araújo et al, 2012). As a result, identifying and regular monitoring of hearing has been recommended (Eloff, 2010; Assuiti et al, 2013). To detect a hearing loss, HIV-positive individuals can visit an audiologist for a diagnostic audiometric assessment but these services can be lengthy, costly and may not be easily accessible. Furthermore, it has been reported that there is <1 audiologist available per million population in the African region (WHO, 2013). Also, those from underserved and rural areas often have many financial expenses and have to travel long distances to get to hospitals for health-care services (Swanepoel and Hall, 2010). In low- and middle-income countries where health-care services are unavailable or unaffordable, hearing loss can lead to an economic burden on the resources of communities and countries (Olusanya et al, 2006; Swanepoel et al, 2010a). With the increased use of technology and access to global connectivity, hearing health access can move beyond the reliance on expensive audiometric booths and equipment (Clark and Swanepoel, 2014). Through decentralization, audiological services may more readily reach these individuals by using mobile health (mHealth) tools through cellular phones and networks (Louw et al, 2017). The use of cell phones and cellular networks have rapidly increased worldwide, making access to hearing health services possible in rural areas (Potgieter et al, 2016; Internet World Stats, 2016). There has been a growing demand for the use of tele-audiology, which led to the development of audiological applications (Swanepoel et al, 2010a; Clark and Swanepoel, 2014). The use of mHealth solutions for hearing testing has been demonstrated to be mobile and affordable at a primary health-care level (Margolis and Morgan, 2008; Swanepoel et al, 2010b; Van Der Aerschot et al, 2016). Such technologies could improve access to hearing health services in an ID clinic setting by providing an inexpensive alternative to a conventional screening or diagnostic audiometry (Margolis and Morgan, 2008; Swanepoel et al, 2014).

An example of an inexpensive mHealth audiometry tool is the validated hearTest™ smartphone application (Sandström et al, 2016; van Tonder et al, 2017). The smartphone application can be self-administered and demonstrates hearing thresholds similar to conventional manual air-conduction audiometry by using a low-cost smartphone (Android Operating System) and calibrated headphones (Van Der Aerschot et al, 2016; van Tonder et al, 2017). The application has a data storage feature, where results can be uploaded to a cloud-based server (van Tonder et al, 2017). This allows for monitoring or surveillance of patients' results over time that can be carried out automatically from the server to flag cases where there may be a drop in hearing sensitivity. The application also has real-time environmental noise monitoring that allows for quality control to be conducted onsite and remotely using a cloud-based management platform (Swanepoel et al., 2014). This type of technology offers potential advantage for use in ID clinic settings that could increase access to hearing detection and surveillance services in these clinics (Margolis and Morgan, 2008; van Tonder et al, 2017).

Another inexpensive mHealth tool that can be used to detect a hearing loss is a simple speech-in-noise test known as the South African English digits-in-noise (DIN) test. This smartphone application is a screening tool that makes use of digits and uses a "closed-set" design with low linguistic demands (Potgieter et al, 2016; 2018). The test is representative of everyday speech-in-noise environments and is ecologically valid to detect the presence of a sensorineural hearing loss, and it does

not require calibrated headphones (Smits et al, 2004; Smits and Houtgast, 2005; Smits et al, 2013; Potgieter et al, 2016). The digits were presented in English, a language similar to other spoken languages and understood by most participants (Branford and Claughton, 2002). The DIN test gives results in signal-to-noise ratio (SNR), which can be used as a baseline for surveillance of hearing in an ID clinic setting.

Both mHealth tools are examples of inexpensive and portable technology that can decrease the need for hearing services in an ID clinic setting in an affordable and mobile way. By implementing an mHealth tool such as hearTest™ or South African English DIN test could allow decentralized service delivery to a population at risk for hearing loss, such as those infected with HIV and TB attending the ID clinic (Keidser and Convery, 2016; Louw et al, 2017). As higher frequencies tend to worsen first in HIV-positive individuals because of ototoxicity, it may be beneficial to select a protocol that includes high frequencies (Fausti et al, 1994; Chandrasekhar et al, 2000; Khoza-Shangase, 2010; van der Westhuizen et al, 2013). Also, lower frequencies are more sensitive to environmental noise which may affect results if it was included in a clinical setting (Mahomed-Asmail et al, 2016). Given that both hearTest™ and the South African English DIN test can detect the presence of a hearing loss, the study will determine the validity and clinical utility of these two smartphone applications in an ID clinic setting for monitoring purposes. The study aimed to determine the current clinical utility of smartphone-automated pure-tone audiometry (PTA) with calibrated headphones and smartphone-based DIN test in an ID clinic when compared with manual audiometry in a feasible and time efficient way.

MATERIALS AND METHODS

Institutional review board clearance was obtained before any data collection commenced. All participants provided written informed consent. Data collection took place at the ID clinics at two tertiary referral hospitals in Gauteng, South Africa.

Participants

All participants who visited these ID clinics were diagnosed with HIV, and recruited. A power analysis was conducted indicating a minimum of 150 subjects should be tested; therefore, the sample consisted of 200 HIV-positive individuals with a mean age of 41.5 years (8.69 standard deviation [SD]). Seventy-three percent of the participants were female and 27% were male. Data were collected at two ID clinics for sampling purposes. An average of 83 HIV-positive individuals visit the first ID clinic, and an average of five HIV-positive individuals visit the second ID clinic per day. Data collection took place between February and May 2017.

Equipment

Otoscopy was conducted using a Welch Allyn 719 Series Lithium Ion Power Handle otoscope, and tympanometry was performed using a 226-Hz probe tone GSI Tympstar, Grason–Stadler tympanometer.

Smartphone audiometry data were collected with a Samsung Galaxy A3 smartphone running the hearTest™ (hearX group, Pretoria, South Africa) Android Operating System (v4.3) application. Supraaural Sennheiser HD 280 Pro headphones (Sennheiser, Wedemark, Germany) were used, calibrated according to reference equivalent threshold sound pressure levels (RETSPL), adhering to equivalent threshold sound pressure levels identified for this headphones according to Madsen and Margolis (2014). Only high frequencies were selected for the protocol which included 2, 4, and 8 kHz. Pure tones were limited up to 90 dB HL at 2 and 4 kHz and up to 80 dB HL at 8 kHz. The lowest stimulus level that was presented was 10 dB HL at all selected frequencies.

DIN testing (South African English DIN test smartphone Application) was conducted on a Samsung Galaxy S6 device with Samsung S6 insert earphones. This mobile application measures the participant's speech recognition threshold (SRT) with a measurement error of 0.7 dB, through changing levels of long-term average speech-spectrum noise by a 2 dB up and down adaptive procedure (Potgieter et al, 2016; 2018). The test included a series of three numbers from zero to nine, known as triplet digits being presented to the participant binaurally, for example 4-7-1.

Manual threshold audiometry was performed using the KUDUwave (MoyoDotNet, Johannesburg, South Africa) Type 2 Clinical Audiometer (IEC 60645-1/2). This tool has been validated to be used outside a sound-treated room and was used as opposed to the gold standard as a practical validated audiometric test in the clinics (Maclennan-Smith et al, 2013; Storey et al, 2014). The KUDUwave software was operated from a notebook computer (Acer Aspire E1-532, running Microsoft Windows 8). The audiometer hardware was encased in the circumaural earcups and was powered by a USB cable plugged into the notebook. The audiometer was calibrated according to international standards organization (ISO) 389-5:2006 before data collection. The circumaural cups covered the transducer earphones after insertion. The insert earphones were calibrated according to ISO 389-2. A response button was connected to the KUDUwave device, which recorded the participant's response. The circumaural earcups have incorporated microphones

which measured ambient noise levels during testing. The same frequencies as for smartphone-automated PTA were tested with manual audiometry.

Procedures

The testing was conducted in a quiet room provided by the clinics. The hearTest™ application integrates noise monitoring referenced to maximum permissible ambient noise levels during the assessment. The noise levels did not exceed the maximum permissible ambient noise levels, as noise concerns would be expected more at 0.5 and 1 kHz. Otological examinations (otoscopy and tympanometry) were carried out first, followed by smartphone-automated PTA, DIN testing, and manual audiometry, in this given order. Fifty participants were retested with smartphone-automated PTA and DIN testing.

The otologic examination was performed by the first author who is a qualified audiologist to identify participants that presented with any abnormal ear canal or tympanic membrane findings. Participants that presented with an atypical finding in otoscopy and tympanometry were excluded from the study, as the DIN test is insensitive to detect conductive hearing loss (Smits and Houtgast, 2005). Participants that presented with a conductive component were referred for necessary intervention.

Instructions were provided, and the participants were seated with their backs facing the tester. Headphones were placed on the participants' ears, and the test started at 2 kHz at 40 dB HL. Testing automatically began in the left ear, unless a participant indicated the right ear is the better hearing ear. If a patient was responding reliably in the initial testing sequences, subsequent frequency testing commenced at 30 dB HL. This was to decrease test time for patients with normal hearing. If a participant pressed the "on-screen button" after the tone was heard, it was recorded as a positive response and the tone would automatically decrease by 10 dB. If a participant did not respond when a stimulus was presented, it was registered as a negative response and the tone would automatically increase by 5 dB. A positive response was recorded as a threshold on the application when two of three responses occurred at the same intensity with three ascents. When test intensities exceeded 40 dB HL, contralateral masking was presented in the opposite ear as specified in ISO 8253:1. Testing was conducted until a minimum of 10 dB HL as noise levels in the health-care setting can make testing >10 dB HL almost impossible (van Tonder et al, 2017).

For the DIN test, the participant was required to adjust the noise on the application to a comfortable hearing level. The participant then had to press the "Start Test" button to begin the test. Triplet digits were presented and a pop-up keyboard appeared to allow the participant to enter the numbers heard. The triplet digits were presented and the participant entered the triplet heard correctly, the next triplet was introduced at 2 dB lower SNR and for an incorrect response at a 2 dB higher SNR. The SRT was calculated as the average SNR from the fourth to the last of the triplets presented. Results were recorded in SNR after the test was initiated.

Manual threshold audiometry was performed to compare thresholds of smartphone audiometry and manual audiometry. Insert earphones were placed into the ear canal, and headphones were put on the participants' ears. Only air-conduction thresholds were measured. The test began at 2 kHz, 30 dB HL. Testing was carried out according to the modified Hughson-Westlake method at 2, 4, and 8 kHz by increasing in steps of 5 dB and decreasing in steps of 10 dB to find a true threshold. Appropriate masking was used for air-conduction when the threshold in the nontest ear obtained exceeds the interaural attenuation (ASHA, 2005).

Data Analysis

A comparative analysis was performed between thresholds obtained from the smartphone application and conventional audiometry using SPSS v.22 (IBM Corporation, Armonk, NY) and MS Excel. The data were not normally distributed. Therefore, a nonparametric analysis (Wilcoxon signed-rank test) was used to determine if there were significant differences between smartphone audiometry and manual audiometry ($p < 0.05$). A total of 1,200 thresholds were obtained across 2, 4, and 8 kHz. The testing was only conducted down to a minimum of 10 dB HL. Thus, all results were analyzed to account for the possible influence of a floor effect. These results are visible in all the tables except Figures 1 and 2. Threshold data for smartphone audiometry and manual audiometry were analyzed descriptively for average differences, average absolute differences, and respective distributions. High-frequency pure-tone average (2, 4 and 8 kHz) of the better ear in each participant was calculated for comparison with the DIN test. Corresponding thresholds between smartphone audiometry and manual audiometry were determined and expressed as a percentage of cases within 5 dB, within 10 dB, and differing by 15 dB or more, as well as for the test–retest measures in smartphone-automated PTA. The Spearman rank correlation test ($p < 0.05$) for nonparametric data was used to determine the test–retest reliability and of both smartphone audiometry and DIN testing, as well as for the relationship between DIN test, manual audiometry and smartphone-automated audiometry.

RESULTS

Participants with a high-frequency pure-tone average >15 dB HL in either ear were defined to have a

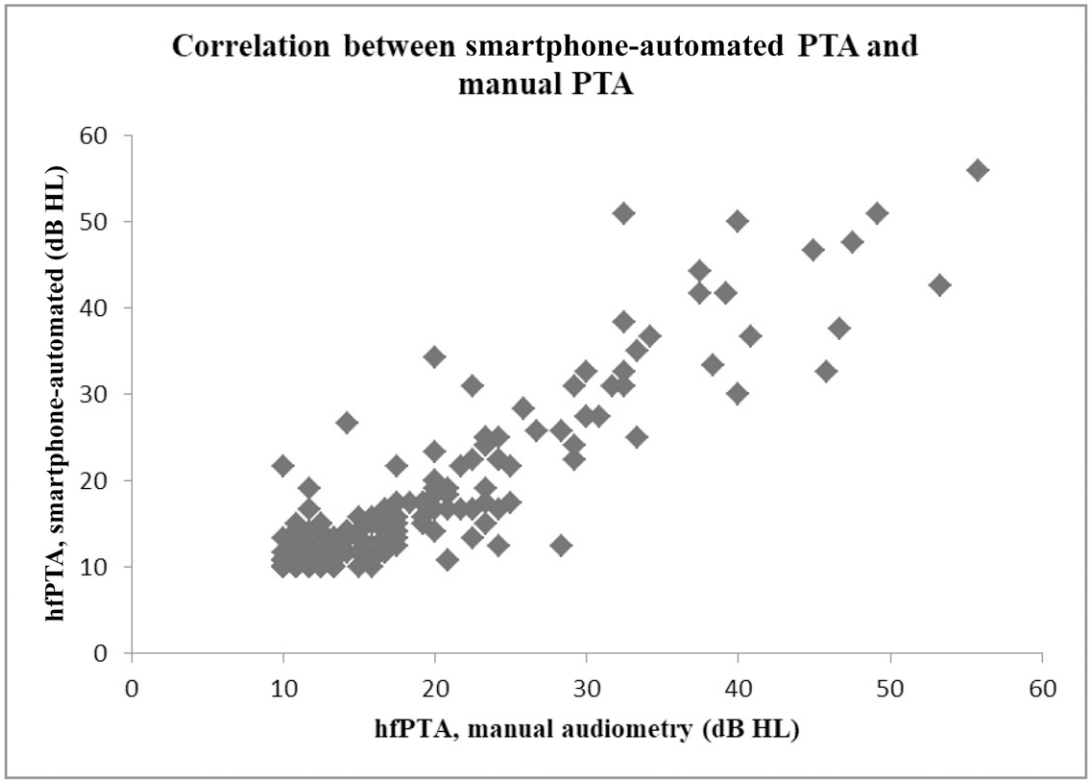

Figure 1. Correlation between smartphone-automated PTA and manual audiometry: Scatter plot of the high-frequency pure-tone average of smartphone-automated PTA versus manual audiometry.

hearing loss. Among participants, 106 subjects (53%) presented with a hearing loss when smartphone audiometry was used and 96 (48%) when manual audiometry was used.

A strong positive correlation between smartphone-automated PTA and manual audiometry was evident ranging from 0.76 to 0.79 across frequencies (Figure 1). Analysis on the smartphone-automated PTA was conducted, which indicated that 37.5% of thresholds were not affected by the floor effect (Table 1) at a minimum response level at 10 dB HL. Means and SDs for both smartphone audiometry and manual audiometry ranged from 26.1 (12.0 SD) to 33.1 (15.7 SD) (Table 2). A statistically significant difference was evident between the right ear of 4 and 8 kHz for smartphone compared with manual audiometry ($p < 0.05$), as well as in the left ear at 4 kHz between smartphone and manual audiometry (Table 3). However, the majority (88.2%) of thresholds differed by 10 dB or less (Table 3). Threshold differences between smartphone audiometry and manual audiometry ranged between −1.7 (9.3 SD) and 4.4 (SD = 11.0). Absolute average differences (Table 3), excluding the floor effect, varied between 4.2 (4.1 SD) and 8.6 (10.3 SD). The mean false positive rate for smartphone-automated PTA was 3.1% (4.9 SD), which indicated that participants responded consistently. If a participant responded when no stimulus was presented, it is considered as a false response and is logged as such by the application. A moderate positive correlation ($r = 0.42$) was present between manual audiometry and the DIN SRT (Figure 2).

No significant difference was noted ($p < 0.05$) between test and retest thresholds of smartphone audiometry. A moderate to strong positive correlation was evident across all frequencies between test–retest thresholds of smartphone audiometry ranging from 0.44 to 0.88 (Table 4). Eighty-five point eight percent (103/120) of thresholds corresponded within 0 to 5 dB between the initial test and retest with smartphone audiometry. The absolute average difference between the test–retest measures of DIN testing was 1.2 dB SNR (1.5 SD). No significant difference was noted in the test–retest measures of the DIN test ($p < 0.05$). A correlation coefficient of 0.56 was present in the DIN test–retest measures when the Spearman rank correlation test was administered. Smartphone-automated PTA took an average of 4:07 min (11 seconds SD) to complete and the DIN test an average of 3:54 min (26 seconds SD) (Table 5).

DISCUSSION

mHealth technology may provide affordable, mobile access to hearing test services that can improve clinical efficiency in settings where the risk of hearing

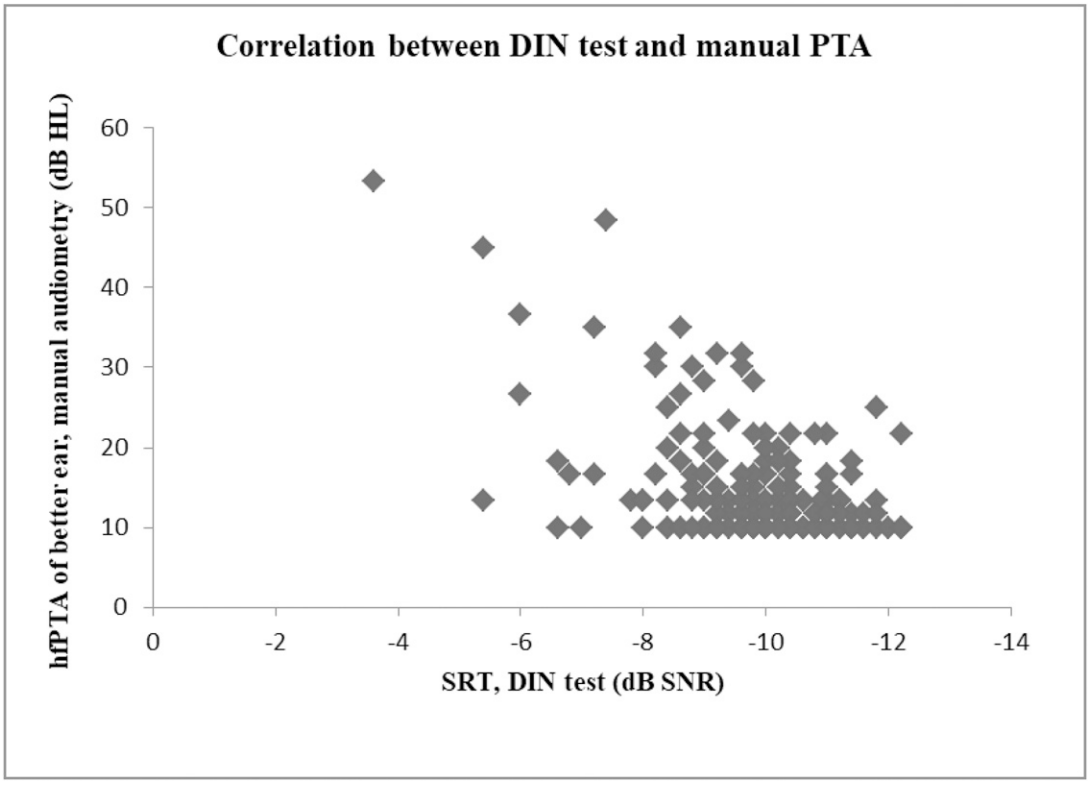

Figure 2. Correlation between DIN test and manual audiometry: Scatter plot of the SRT from DIN test versus the high-frequency puretone average of the better ear in manual audiometry.

loss may be high, such as an ID clinic. We aimed to evaluate the clinical utility of smartphone-automated PTA and DIN test in an ID clinic. The present study indicated good reliability for the use of smartphone applications in an ID clinic. By evaluating the clinical utility of any novel tool, the mobile applications should be compared with the gold standard conventional audiometry (Bland and Altman, 1999). In this case, a clinical audiometer (KUDUwave) was used as the reference test because it has been validated for use in controlled environments outside a sound booth (Maclennan-Smith et al, 2013). This comparative reference test, although validated for use outside a sound booth, is limited by the fact that it was not conducted in a typical sound booth adhering to required maximum permissible ambient noise levels.

Table 1. Distribution of Thresholds for Smartphone-Automated PTA and Manual Audiometry

		Frequencies (kHz)		
		% (n)		
		2	4	8
Right	Automated and conventional = 10 dB	39.5 (79)	41.5 (83)	38.5 (77)
	Automated >10 dB and conventional = 10 dB	12 (24)	23.5 (47)	4 (8)
	Automated = 10 dB and conventional >10 dB	12.5 (25)	5.5 (11)	12.5 (25)
	Automated >10 dB and conventional >10 dB	36 (72)	29.5 (59)	45 (90)
Left	Automated and conventional = 10 dB	24.5 (49)	41.5 (83)	37 (74)
	Automated >10 dB and conventional = 10 dB	31 (62)	25.5 (51)	9 (18)
	Automated = 10 dB and conventional >10 dB	4 (8)	1.5 (3)	11.5 (23)
	Automated >10 dB and conventional >10 dB	40.5 (81)	31.5 (63)	42.5 (85)
Total	Automated and conventional = 10 dB	32 (128)	41.5 (166)	37.75 (151)
	Automated >10 dB and conventional = 10 dB	21.5 (86)	24.5 (98)	6.5 (26)
	Automated = 10 dB and conventional >10 dB	8.25 (33)	3.5 (14)	12 (48)
	Automated >10 dB and conventional >10 dB	38.25 (153)	30.5 (122)	43.75 (175)

Table 2. Means (SD) for Smartphone-Automated PTA and Manual Audiometry Thresholds Unaffected by the Floor Effect

		Frequency (kHz)		
		2	4	8
Right	Smartphone-automated audiometry	26.4 (13.4)	29.7 (13.0)	28.8 (13.5)
	Manual audiometry	26.9 (15.4)	27.3 (16.1)	31.7 (15.9)
Left	Smartphone-automated audiometry	26.1 (12.0)	33.1 (15.7)	31.9 (17.7)
	Manual audiometry	25.4 (14.5)	26.9 (16.5)	32.3 (17.6)
Total	Smartphone-automated audiometry	26.2 (12.7)	31.5 (14.5)	30.3 (15.7)
	Manual audiometry	26.1 (14.9)	27.1 (16.3)	32.0 (16.7)

Hearing threshold variation between two methods of hearing assessment is accepted as subclinical within context when compared with conventional audiometry if hearing thresholds vary by 10 dB or less (OSHA, 1983; McDaniel et al, 2017). A significant statistical difference was seen at 4 and 8 kHz ($p < 0.05$); however, the majority of thresholds (88.2%) of those unaffected by the floor effect corresponded within 10 dB or less between smartphone-automated PTA and manual audiometry. This is in line with a study carried out by Mahomed-Asmail et al (2016), which showed a correspondence of 87.7% between automated audiometry and conventional audiometry. There are some possible reasons for the significant differences in thresholds between the smartphone and conventional audiometry. These may include slight calibration differences between the circumaural headphones (smartphone) and insert earphones (conventional), smartphone testing was a self-operated automated procedure whereas manual audiometry was conducted by an audiologist. Furthermore, the insert earphone covered by circumaural earcup for the manual audiometry offers more attenuation to environmental noise, which may also have influenced threshold differences in this context outside a sound booth.

Table 3. Average, Absolute Average Differences*, and Correspondence between Automated and Manual Audiometry per Frequency Excluding the Floor Effect

			Frequency (kHz)		
			2	4	8
Right ear	Threshold comparison excluding the floor effect (n)		72	59	90
	Average difference (dB)	Mean	−0.5	2.5**	−3.0**
		SD	5.9	9.6	9.3
	Absolute average difference (dB)	Mean	4.3	6.5	6.6
	SD	SD	4.1	7.4	7.3
	Correspodence (%)	0–5 dB	84.7	62.7	70
		±10 dB	9.7	20.3	18.9
		≥15 dB	5.6	16.9	11.1
Left ear	Threshold comparison excluding the floor effect (n)		81	63	85
	Average difference (dB)	Mean	0.7	6.2**	−0.4
		SD	7.3	11.9	9.1
	Absolute average difference (dB)	Mean	4.4	8.6	5.8
	SD	SD	5.8	10.3	7.0
	Correspodence (%)	0–5 dB	86.4	58.7	76.5
		±10 dB	7.4	17.5	14.1
		≥15 dB	6.2	23.8	9.4
Total	Threshold comparison excluding the floor effect (n)		153	122	175
	Average difference (dB)	Mean	0.1	4.4**	−1.7**
		SD	6.6	11.0	9.3
	Absolute average difference (dB)	Mean	4.3	7.6	6.2
	SD	SD	5.0	9.1	7.1
	Correspodence (%)	0–5 dB	85.6	60.7	72.6
		±10 dB	8.5	18.9	16.6
		≥15 dB	5.9	20.5	10.9

Notes: *Manual subtracted from automated audiometry thresholds.

**Significant difference ($p < 0.05$)

Table 4. Test–Retest Reliability of Automated Audiometry Excluding the Floor Effect

		Frequency (kHz)		
		2	4	8
	n	18	15	13
Right ear	Mean difference (test minus retest)	1.4	2.7	0.0
	SD	7.4	7.3	7.9
	Absolute difference	4.2	4.0	5.4
	SD	6.2	6.6	5.6
	Correlation coefficient (*r*)	0.70	0.76	0.68
	0–5 dB difference (%)	83.3	87	77
	10 dB difference (%)	11.1	7	15
	>15 dB difference (%)	5.6	7	8
	n	30	25	19
Left ear	Mean diff (test minus retest)	1.7	2.8	3.2
	SD	6.1	13.2	8.5
	Absolute difference	2.7	7.6	4.2
	SD	5.7	11.1	8.0
	Correlation coefficient (*r*)	0.88	0.44	0.83
	0–5 dB difference (%)	96.7	76	89
	10 dB difference (%)	0.0	8	5
	>15 dB difference (%)	3.3	16	6
	n	48	40	32
Total	Mean diff (test minus retest)	1.6	2.8	1.9
	SD	6.5	11.3	8.3
	Absolute difference	3.2	6.3	4.7
	SD	5.9	9.7	7.1
	Correlation coefficient (*r*)	0.83	0.55	0.80
	0–5 dB difference (%)	91.7	80.0	84.4
	10 dB difference (%)	4.2	7.5	9.4
	>15 dB difference (%)	4.2	12.5	6.3

Several studies have compared automated or smartphone audiometry with conventional or manual audiometry in various settings, although none have been conducted in an ID clinic environment (Margolis et al, 2011; Mahomed-Asmail et al, 2013; Peer and Fagan, 2015; Sandström et al, 2016; van Tonder et al, 2017). Threshold differences between automated and manual audiometry reported in a meta-analysis ranged between −5.0 dB (8.7 SD) and −0.1 dB (5.5 SD) across frequencies 2, 4, and 8 kHz, on the validity of automated and manual audiometry (Mahomed-Asmail et al, 2013). Mean differences in the present study were in line with the meta-analysis and for results reported by van Tonder et al (2017) that ranged from −3.3 dB (6.2 SD) to 1.6 dB (6.6 SD), as well as for Margolis et al (2011) and Sandström et al (2016). However, variability (SD's) is seen to be higher at 4 and 8 kHz compared with these studies.

Mean differences for test–retest measures of smartphone-automated PTA were comparable with mean differences between smartphone and manual audiometry thresholds in the present study. Mahomed et al (2013) reported mean differences from 0.0 dB (6.4 SD) to 0.7 (7.1 SD) in test–retest reliability differences between 2 and 4 kHz in automated audiometry. Similar variability (SD's) was reported in the present study. Swanepoel and Biagio (2011) compared computer-based audiometry with conventional audiometry and found similar absolute average differences that ranged from 3.0 to 3.3. However, higher variability was observed in this study at 4 and 8 kHz. By contrast, test–retest thresholds have a strong positive correlation, and test–retest differences

Table 5. Mean Test Durations of Mobile Applications

	Automated	Automated (Retest)	DIN Test
Mean (seconds)	273	247	234
SD	49	11	26
Min−Max (seconds)	108−794	99−675	142−444

fall within the 0–5 dB range 88% of the time. Also, mean test–retest differences were <2 dB, and the absolute average differences were <4 dB. Therefore, smartphone–automated PTA is a reliable mHealth tool to monitor hearing in an ID clinic setting.

A moderate positive relationship for test–retest reliability was observed in DIN testing ($r = 0.56$). By contrast, Rashid et al (2017) found higher correlation coefficients ($r = 0.74$) in an occupational setting using a speech-in-noise test in high-frequency hearing losses. The differences between the studies may suggest that the DIN test has a possible learning effect, which was also reported by Smits et al (2013). Rashid et al (2017) showed a mean difference between test–retest measures of 0.3 dB SNR (1 SD), which is in line with the present study. Strong correlations between SRTs and pure-tone averages in high frequencies were observed in various studies (Jansen et al, 2013; Leensen and Dreschler, 2013; Rashid et al, 2017). In these studies, DIN or speech-in-noise tests were implemented in occupational settings to screen for a noise-induced hearing loss. A lower correlation coefficient that was observed in the present study may be because of the procedures of the other studies that were adapted to screen for higher frequency hearing losses. These studies also had different language and speech material, for example, Dutch consonant–vowel–consonant combinations containing high-frequency consonants (Jansen et al, 2013; Leensen and Dreschler, 2013; Rashid et al, 2017). The test frequencies in the present study also differed from these previous studies that included frequencies from 2, 3, 4, and 6 kHz.

The total time for smartphone-automated PTA and DIN test only differed by 39 seconds. By taking the time and coverage rate into consideration, an ID clinic could test >80 individuals per day with these smartphone applications, depending on the working hours of an ID clinic. Health-care workers or nurses available in the clinic can be minimally trained to facilitate the test in a quiet environment (Yousuf Hussein et al, 2015). As both tests were self-administered, trained staff can also test patients for monitoring purposes during patients' monthly visits.

A limitation of the present study is the order of the tests that were not randomized and may have influenced the results. As smartphone-automated PTA was administered first, it is expected for the thresholds to be higher than those of manual audiometry. Therefore, it is recommended that future research should implement a counterbalanced order in their method of testing. In DIN testing, results were binaural and not ear specific. This may be a clinical implication for the future if a unilateral hearing loss is present. Future research can adapt the test procedure to get ear-specific results and may prevent missing a one-sided hearing loss. In test–retest measures for DIN testing, participants did not receive a training list before the evaluation; it is, therefore, recommended in future to include such a list.

In the HIV population, higher frequencies appear to be affected first, with hearing loss spreading to the conventional frequency range through the progression of the disease and the course of treatment of ototoxic medications (Fausti et al, 1994). In the present study, it is evident that participants did not show typical high-frequency hearing losses. This may be because of the relatively young sample that was present as the mean age is 44.4 years. Moreover, most patients may have recently started with ARV medication. Furthermore, these patients are required to visit the clinic monthly, which improves their immune system due to the use of ARVs. Ototoxicity might also be more prevalent in patients that concurrently use a combination of ARVs together with medications prescribed for opportunistic infections. However, the present study aimed to determine the feasibility of the mobile hearing applications for future monitoring purposes. Recommendations for future research in the clinical utility of smartphone hearing applications in an ID clinic setting could implement a protocol that extends testing of PTA in higher frequencies (16 kHz and higher). Early detection of ototoxicity in assessing higher frequencies can lessen communication deficit and reduce the risk of ototoxicity, as higher frequencies are essential for verbal communication (Fausti et al, 1994). Clinical health workers can manage an ototoxicity-monitoring program to implement in an ID clinic setting along with an audiologist for necessary intervention.

CONCLUSION

The use of smartphone-automated PTA could be a portable, inexpensive, practical, and accessible alternative to manual audiometry in ID clinic settings (Foulad et al, 2013; Clark and Swanepoel, 2014). Based on the results, smartphone-automated PTA demonstrates better reliability than the DIN test to implement in an ID clinic setting. The smartphone application could be used as a rapid baseline and monitoring tools for ototoxicity for patients attending an ID clinic.

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