Extended High-Frequency Smartphone Audiometry: Validity and Reliability

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Abstract

Background: Extended high-frequency (EHF) audiometry (8–16 kHz) has an important role in audiological assessments such as ototoxicity monitoring, and for speech recognition and localization. Accurate and reliable EHF testing with smartphone technologies has the potential to provide more affordable and accessible hearing-care services, especially in underserved contexts.

Purpose: To determine the accuracy and test–retest reliability of EHF audiometry with a smartphone application, using calibrated headphones.

Research Design: Air-conduction thresholds (8–16 kHz) and test–retest reproducibility, recorded with conventional audiometry (CA) and smartphone audiometry (SA), using audiometric (Sennheiser HDA 300 circumaural) and nonstandard audiometric (Sennheiser HD202 II supra-aural) headphones, were compared in a repeated-measures design.

Study Sample: A total of 61 participants (122 ears) were included in the study. Of these, 24 were adults attending a tuberculosis clinic (mean age = 36.8, standard deviation [SD] = 14.2 yr; 48% female) and 37 were adolescents and young adults recruited from a prospective students program (mean age = 17.6, SD = 3.2 yr; 76% female). Of these, 22.3% (n = 326) of EHF thresholds were ≥25 dB HL.

Data Analysis: Threshold comparisons were made between CA and SA, with audiometric headphones and nonstandard audiometric headphones. A paired samples *t*-test was used for comparison of threshold correspondence between conventional and smartphone thresholds, and test–retest reproducibility of smartphone thresholds.

Results: Conventional thresholds corresponded with smartphone thresholds at the lowest intensity (10 dB HL), using audiometric and nonstandard audiometric headphones in 59.4% and 57.6% of cases, respectively. Conventional thresholds (exceeding 10 dB HL) corresponded within 10 dB or less, with smartphone thresholds in 82.9% of cases using audiometric headphones and 84.1% of cases using nonstandard audiometric headphones. There was no significant difference between CA and SA, using audiometric headphones across all frequencies ($p > 0.05$). Test–retest comparison also showed no significant differences between conditions ($p > 0.05$). Smartphone test–retest thresholds corresponded within 10 dB or less in 86.7% and 93.4% of cases using audiometric and nonstandard audiometric headphones, respectively.

Conclusions: EHF smartphone testing with calibrated headphones can provide an accurate and reliable option for affordable mobile audiometry. The validity of EHF smartphone testing outside a sound booth as a cost-effective and readily available option to detect high-frequency hearing loss in community-based settings should be established.

Key Words: aging, automated audiometry, diagnostic audiometry, extended high frequencies, mHealth, noise-induced hearing loss, ototoxicity, smartphone

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The University of Pretoria has assigned the IP of the hearTest smartphone application for commercialization by the hearX group (Pretoria, South Africa). The second author has declared an involvement with the hearX group (equity, consulting, potential royalties).

Abbreviations: CA = conventional audiometry; EHF = extended high frequency; NIHL = noise-induced hearing loss; SA = smartphone audiometry; SD = standard deviation

INTRODUCTION

The Global Burden of Disease Study indicated that 1.23 billion people lived with some form of hearing loss in 2015 (Vos et al, 2016). The results showed that hearing loss has moved from the 11th leading cause of years lived with disability in 2010 to the 4th leading cause in 2015 (Vos et al, 2012; 2015; 2016; Wilson et al, 2017). More specifically, the prevalence of a disabling loss of hearing, in both children and adults was thought to be higher in developing regions, such as the Asia-Pacific area, southern Asia, and sub-Saharan Africa (Stevens et al, 2011; Olusanya et al, 2014; Mulwafu et al, 2017). Several factors contribute to the increasing global prevalence of disabling hearing loss. One contributor is age-related hearing loss with average life expectancies increasing globally (Olusanya et al, 2014). Approximately, 15% of the world's adult population has some degree of hearing loss, 25% of whom are more than 65 yr of age (WHO, 2013). Apart from age-related hearing loss, other factors contributing to hearing loss are exposure to noise and ototoxic medications (Arslan et al, 1999; Fuente and Hickson, 2011; Basner et al, 2014; Olusanya et al, 2014).

Noise exposure remains a leading cause of sensorineural hearing loss in occupational settings (Palmer et al, 2002; Nelson et al, 2005; Mehrparvar et al, 2011; Basner et al, 2014; Olusanya et al, 2014). The rapid urbanization in many emerging economies, together with the lack of enforceable regulations on environmental and occupational noise, adds to this public health issue (Basner et al, 2014; Olusanya et al, 2014). There has also been a growing concern regarding unsafe noise levels in nonoccupational settings, such as social and environmental noise (Serra et al, 2005). WHO (2015a,b) estimates that 1.1 billion teenagers and young adults are at risk for developing a hearing loss because of unsafe use of personal audio devices and of recreational events, such as night clubs and sport events.

Not only can excessive noise damage hearing, but medications used to treat neonatal infections, malaria, cancer, human immunodeficiency virus infection, and tuberculosis can also cause auditory and/or vestibular dysfunction, which may lead to a permanent hearing loss (Durrant et al, 2009; Harris et al, 2012; Olusanya et al, 2014; Mulwafu et al, 2017). The combination of exposure to ototoxic medications and noise exposure, either occupational or social, may have further compounding effects on hearing sensitivity (Langer et al, 2013; Davis et al, 2016).

Age-related hearing loss, noise-induced hearing loss (NIHL), and ototoxicity may be observed as a high-frequency hearing loss that gradually progresses toward lower frequencies (Durrant et al, 2009; Seddon et al, 2012; Mehrparvar et al, 2014). The acoustic energy of extended high frequencies (EHFs) plays an important role in speech perception, especially in the presence of background noise (Rodríguez Valiente et al, 2014; Vitela et al, 2014; Vlaming et al, 2014). Despite this, the gradual change in hearing sensitivity may, initially, go unnoticed, as hearing perception is dominated by low-frequency hearing (Vlaming et al, 2014). This, coupled with the slow progression of hearing loss, means that individuals often wait too long to seek help, despite presenting with communication difficulties in certain situations (Vlaming et al, 2014). Early detection may be most effectively accomplished by monitoring hearing sensitivity at the highest audible frequencies (9–20 kHz), before hearing loss progresses toward the conventional audiometric frequencies (0.125–8 kHz) most relevant for speech understanding (Gordon et al, 2005; Durrant et al, 2009; Harris et al, 2012; Jacobs et al, 2012; Rodríguez Valiente et al, 2014; Vlaming et al, 2014).

EHF audiometry is well established as an early detection tool for possible ototoxic hearing loss, with a growing interest in its use for hearing conservation programs (Balatsouras et al, 2005; Somma et al, 2008; Mehrparvar et al, 2011; 2014; Vlaming et al, 2014; Maccà et al, 2015; Liberman et al, 2016). Both ototoxic monitoring and hearing conservation programs aim to detect changes in the cochlea as early as possible. Following acoustic trauma, some authors report a threshold shift at 3–6 kHz with a considerable hearing loss in the EHF range, especially at 14 and 16 kHz (Fausti et al, 1979; Dieroff, 1982; Hallmo et al, 1995; Somma et al, 2008; Mehrparvar et al, 2011; 2014; Maccà et al, 2015). Another study found that EHF audiometry was more sensitive than conventional audiometry (CA) in detecting NIHL (Somma et al, 2008). This study concluded that EHF could be an effective measurement for early detection in young adults who are or have been exposed to noise. By contrast, other studies found EHF provided no significant additional information at 9–14 kHz for early detection of NIHL (Osterhammel and Osterhammel, 1979; Balatsouras et al, 2005; Schmuziger et al, 2007), indicating that the exact effect of noise exposure on EHF thresholds is still not entirely clear (Schmuziger et al, 2007; Vlaming et al, 2014; Liberman et al, 2016).

Despite this lack of consensus, there are clear clinical advantages of EHF audiometry which have the potential to deliver early detection and preventative care. EHF thresholds can be measured using audiometers capable of delivering sounds with sufficient pressure levels, transduced through headphones at the reference equivalent sound pressure levels required for EHFs (Rodríguez Valiente et al, 2014). However, these audiometers are usually only found in private or tertiary

healthcare facilities and are not widely accessible to at-risk patients in rural settings (Swanepoel and Hall, 2010; Swanepoel, Koekemoer, et al, 2010). Ideally, monitoring of hearing thresholds at the EHF range for at-risk patients should be provided at primary healthcare levels or even in the homes of individuals. This is especially relevant for those patients either too infectious or too ill to visit an audiology facility for monitoring, as is often the case with multidrug-resistant tuberculosis patients or patients receiving chemotherapy.

Although recent developments in mobile audiometry are extending the reach of audiologists, the technology is still dependent on standalone hardware, with the option of PC-linked technology, which is often prohibitively expensive, especially in low- and middle-income countries (Swanepoel, Clark, et al, 2010; Swanepoel and Hall, 2010; Swanepoel, Koekemoer, et al, 2010; Swanepoel and Biagio, 2011; Eikelboom et al, 2013). Several studies, including a systematic review and meta-analysis, have compared automated and CA methods and have shown clinical validity (Swanepoel and Biagio, 2011; Mahomed et al, 2013; Sandström et al, 2016; van Tonder et al, 2017), but have been limited to conventional audiometric frequencies (0.5–8 kHz). Jacobs et al (2012) and Dille et al (2013) investigated the effectiveness of a portable PC-based system for detecting and monitoring ototoxicity. The automated (patient self-test) testing across conventional and EHF (0.5–20 kHz) was comparable with CA.

Smartphone audiometry (SA) solutions have been proposed as a way to reduce cost and increase access, while integrating environmental sensors, data capturing, and uploading capabilities (Clark and Swanepoel, 2014; Swanepoel et al, 2014). Recent studies have already demonstrated real promise for the use of smartphone applications for hearing assessment in different populations (Swanepoel et al, 2014; Mahomed-Asmail et al, 2016; Sandström et al, 2016; van Tonder et al, 2017) and validated the use of nonaudiometric supra-aural headphones with established equivalent threshold sound-pressure levels as a cost-effective alternative for hearing screening (Van der Aerschot et al, 2016).

Studies on an Android smartphone application (hearScreen™) demonstrated that a low-cost smartphone with calibrated headphones produced clinical results comparable with conventional school-based hearing screening (Swanepoel et al, 2014; Mahomed-Asmail et al, 2016). Its use in primary healthcare settings (Louw et al, 2017) and community-based screening programs, using minimally trained persons (Yousuf Hussein et al, 2016), has also been validated. Further studies using the technology to assess hearing thresholds have indicated that accurate thresholds could be determined using this technology in conventional clinical settings and at primary healthcare settings (Sandström et al, 2016; van Tonder et al, 2017). Clinical validity of SA for EHF has not been demonstrated, however. This type of smartphone technology that allows for accurate EHF testing can provide screening and monitoring in specific populations. In particular, where diagnostic equipment, such as a clinical audiometer with EHF testing capabilities in a sound booth, is inaccessible. The aim of this study was, therefore, to determine the accuracy and reliability of SA with audiometric headphones, as well as nonstandard audiometric headphones as a possible low-cost solution, for determining EHF thresholds.

METHODS

Clearance from the University of Pretoria's Research Ethics Committee and the Faculty of Natural and Agriculture Sciences Committee for Research (Ref: GW20150324HS), as well as permission from the Director of Clinical Services at Dr. George Mukhari Academic Hospital was obtained before any data collection. A repeated-measures within-subject design (Leedy and Ormrod, 2013) was used to compare hearing thresholds determined by smartphone and conventional EHF audiometry. All participants were tested in the following test conditions: (a) conventional EHF audiometry, with audiometric headphones; (b) smartphone application, with audiometric headphones; (c) smartphone application, with calibrated, nonstandard audiometric headphones; (d) participants underwent a fourth repeated measurement of either one of the three test conditions to determine test–retest reliability.

Participants

A total of 61 participants were included in the study by means of convenience and purposive sampling. Twenty-four were recruited from adults attending the Audiology Department at Dr. George Mukhari Hospital, Ga-Rankuwa, South Africa (group 1: mean age = 36.8, standard deviation [SD] = 14.2 yr; age range = 22–64 yr; 48% female). Of these 24 adults, 41.6% (n = 10) had a history of receiving potentially ototoxic medication. The remaining 37 participants were recruited from the University of Pretoria (group 2: mean age = 17.6, SD = 3.2 yr; age range = 16–23 yr; 76% female). The selection criterion specified the inclusion of hearing sensitivity, that is, ranging from normal hearing to a severe sensorineural hearing loss, to ensure a reasonable distribution of thresholds. Of these, 22.3% (n = 326) of EHF thresholds were ≥25 dB HL. Members of group 1 were evaluated with pure-tone air conduction audiometry, tympanometry, and otoscopy. Members of group 2 were evaluated with pure-tone air conduction audiometry and otoscopy only, as tympanometry was unavailable.

Equipment and Procedures

All hearing threshold measurements were conducted in a sound booth. A diagnostic two-channel audiometer

(GSI 61 Clinical Audiometer, Pretoria, South Africa), with circumaural Sennheiser HDA 200 headphones, was used for the conventional EHF audiometry condition. Audiometric testing equipment was calibrated on May 12, 2014 and according to the South African Bureau of Standards (SANS 10154-1; 10154-2) based on the International Organization for Standardization (ISO) calibration standard (ISO 389-9, 2009). Maximum stimulus levels that the conventional audiometer could reach were 105, 95, 90, and 65 dB HL for 8, 10, 12.5, and 16 kHz, respectively.

For the smartphone test, a Samsung Galaxy Trend Neo smartphone, which runs on Android operating system (v4.0.4), was used. The software used was the hearTest® application (HearX Group, Pretoria, South Africa), a threshold version of the validated hearScreen™ application (Swanepoel et al, 2014; Yousuf Hussein et al, 2016; Mahomed-Asmail et al, 2016; Sandström et al, 2016; Louw et al, 2017), which allows for automated threshold determination at conventional and EHF ranges. Calibration was performed on the calibration feature of the hearTest® application. Minimum stimulus level of 10 dB HL could be delivered with the smartphone across frequencies, and the maximum stimulus levels were 75, 70, 75, and 65 dB HL for 8, 10, 12.5, and 16 kHz respectively. Sennheiser HDA 300 circumaural headphones, calibrated using a plat adapter with an International Electrotechnical Commission (IEC) 60318-1 G.R.A.S. Ear simulator (GRAS Sound & Vibration A/S) and adhering to ISO calibration standards (ISO 389-9, 2009), were used for the audiometric headphones condition. The commercially available Sennheiser HD202 II supra-aural headphones, calibrated using an IEC 60318-1 G.R.A.S. Ear simulator and according to the recently determined equivalent threshold sound-pressure levels by Van der Aerschot et al (2016), were used for the nonstandard audiometric headphone condition.

Data were collected in a cross-sectional manner and on the same day for each participant. EHF (8, 12.5, 14, and 16 kHz) thresholds were determined for each of the four test conditions for every participant. Testing was done in a counterbalanced order so as to ensure that the results were not influenced by the test order. Participants were randomly allocated to a particular test order. The CA condition was conducted by an audiologist (Martelle Bornman). However, the test operator did not view the results before audiometric testing. Participants were asked to respond to a pure-tone signal by pressing a response button. The modified Hughson–Westlake method (Carhart and Jerger, 1959) for determining pure-tone thresholds was used. For the smartphone condition, participants were asked to respond to an automated pure-tone algorithm based on the modified

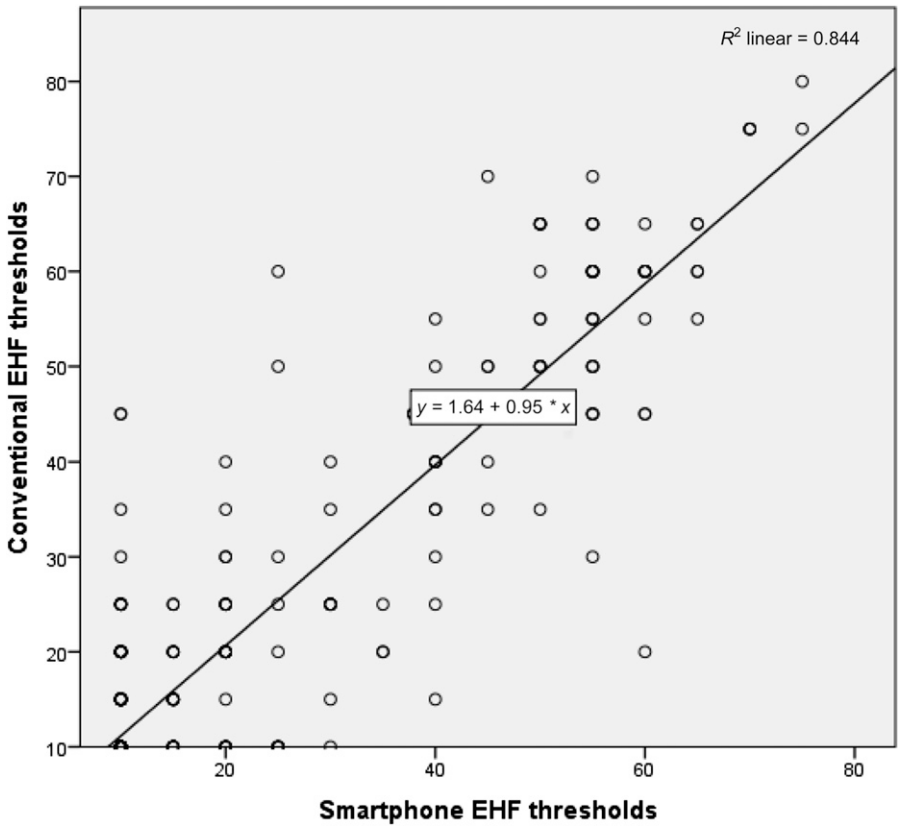

Figure 1. The relationship of thresholds (dB HL) determined with conventional EHF audiometry and smartphone EHF audiometry using audiometric headphones.

Hughson–Westlake method (Carhart and Jerger, 1959) by pressing a virtual response button on the touchscreen of the smartphone.

Analysis

Smartphone testing had certain intensity limitations, as opposed to CA. In the cases where responses could be measured at maximum intensities for one condition and no responses were obtained for another, direct comparisons could not be made. No responses were, therefore, logged as empty cells. As the minimum intensity level for SA was 10 dB HL, CA was limited to test to the same level. To account for a possible floor effect, conventional and smartphone thresholds that were at 10 dB HL, as well as exceeded 10 dB HL, were compared.

Data were recorded and analyzed using Microsoft Excel and SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 23.0; IBM Corp., Armonk, NY). Threshold data for CA and SA (>10 dB HL) were analyzed descriptively for average and average absolute differences and respective distributions. To determine whether threshold differences between conventional and smartphone EHF audiometry were statistically significant, as well as determining the test–retest reliability for the smartphone methods, a paired sample *t*-test was performed. The Bonferroni correction was applied to maintain a statistical probability of $p < 0.05$ as significant.

RESULTS

Out of a possible 959 threshold-seeking instances, there were 12 instances where responses at the maximum intensities could not be measured for smartphone EHF testing, but were obtained at higher intensities through conventional EHF audiometry. There were five threshold-seeking instances where responses at maximum intensities could not be measured for smartphone or for conventional EHF audiometry. These instances were excluded from the analysis.

Figures 1 and 2 demonstrate a strong, positive, linear correlation between conventional EHF audiometry and smartphone EHF audiometry, with correlation values of 0.84, using audiometric headphones and 0.85, using nonstandard audiometric headphones.

In 59.4% of threshold-seeking instances across all test frequencies for audiometric headphones, the participants obtained a 10 dB HL threshold, with both CA and SA (Table 1). This correspondence was 57.6% for nonstandard audiometric headphones. Thresholds, obtained through smartphone and conventional EHF audiometry, differed by ≤5 dB in 77% and 78.4% of threshold-seeking

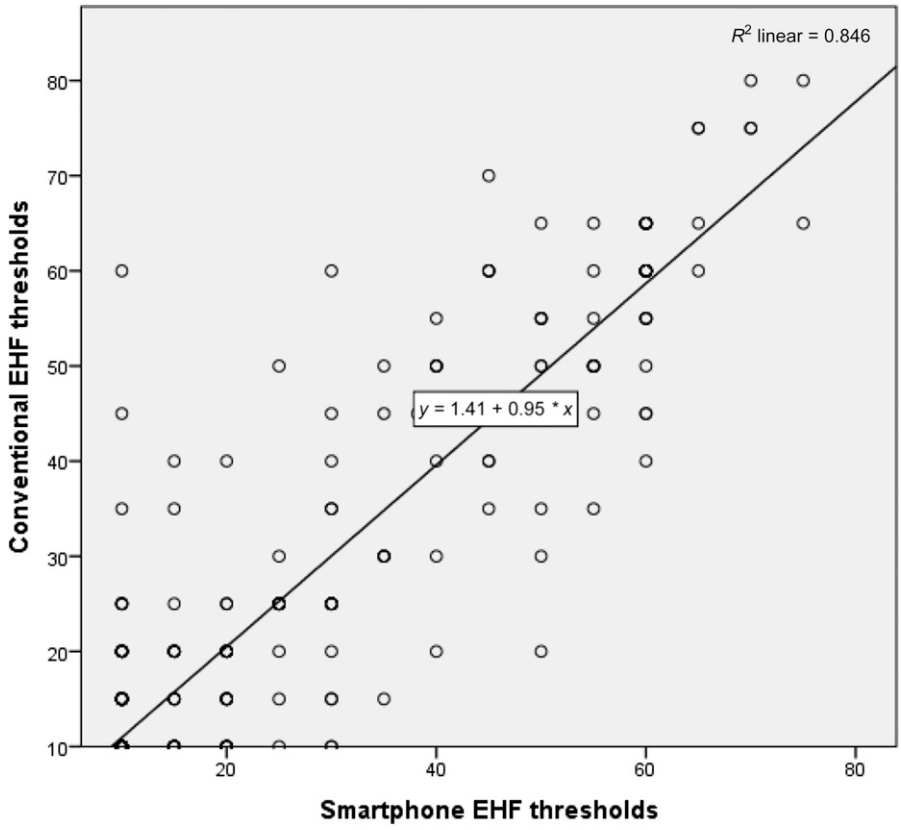

Figure 2. The relationship of thresholds (dB HL) determined with conventional EHF audiometry and smartphone EHF audiometry using nonstandard audiometric headphones.

Table 1. Distribution (%) of Thresholds for CA and SA with Audiometric and Nonstandard Audiometric Headphones

Thresholds	8 kHz	10 kHz	12.5 kHz	16 kHz	All
Audiometric headphones (n = 122)					
10 dB for CA and SA	61.5	61.5	63.9	50.8	59.4
CA and SA > 10 dB	20.5	22.1	23	35.2	25.2
CA > 10 dB and SA = 10 dB	12.3	10.7	9	9.8	10.6
SA > 10 dB and CA = 10 dB	5.7	4.9	2.5	4.1	4.3
Nonstandard audiometric headphones (n = 122)					
10 dB for CA and SA	57.4	64.8	61.5	46.7	57.6
CA and SA >10 dB	22.1	20.5	27.9	42.6	28.3
CA > 10 dB and SA = 10 dB	9	13.1	4.1	5.7	8
SA > 10 dB and CA = 10 dB	9.8	0.8	3.3	4.9	4.7

instances using audiometric and nonstandard audiometric headphones, respectively (Table 2). Conventional thresholds, exceeding the minimum test intensity (10 dB HL), corresponded within 5 dB HL, with smartphone thresholds in 70.2% and 71.6% of cases using audiometric and nonstandard audiometric headphones (Table 2).

The overall average threshold difference, including thresholds at 10 dB HL, for audiometric headphones (1.2 ± 7.9), was poorer than for nonstandard audiometric headphones (0.6 ± 6.3; Table 3). Analysis of the thresholds, excluding those at 10 dB HL, showed the average threshold difference using audiometric headphones (0.9 ± 9.7) to be slightly better than that of nonstandard audiometric headphones (1.4 ± 8.1). The overall average absolute difference, both including and excluding thresholds at 10 dB HL, were within similar ranges across headphones. Excluding the thresholds at 10 dB HL, results showed no significant differences between thresholds for CA and SA, using audiometric headphones across frequencies all ($p > 0.05$). When using nonstandard audiometric headphones for smartphone EHF audiometry and excluding those thresholds at 10 dB HL, the only significant difference was at 10 kHz ($p < 0.05$).

The overall average test–retest difference was similar for both audiometric headphones (0.7 ± 5.9) and nonstandard audiometric headphones (0.7 ± 6.3), and not significantly different to that of CA (0.8 ± 4.2; Table 4). Excluding thresholds at 10 dB HL, audiometric headphones (−1.4 ± 9.4) and conventional EHF audiometry (−0.6 ± 6.0) had lower test–retest difference than nonstandard audiometric headphones (0.2 ± 6.3). Average absolute test–retest reliability differences were similar for audiometric (5.4 ± 7.6) and nonstandard audiometric (5.0 ± 4.2) headphones. Test–retest reliability for smartphone EHF audiometry, using audiometric and nonstandard audiometric headphones, including and excluding thresholds at 10 dB HL, showed no statistically significant differences across all frequencies ($p > 0.05$).

DISCUSSION

The present study is the first to use a smartphone-based audiometry application, with calibrated headphones, to determine thresholds in the EHF range. Study findings demonstrate EHF threshold accuracy and reliability comparable with that of CA.

Most of the thresholds were within the clinically acceptable 10 dB test–retest difference for EHF reported in previous studies (Frank, 1990; Frank and Dreisbach, 1991). Excluding those thresholds at 10 dB HL, 93.4% of smartphone test–retest EHF thresholds,

Table 2. Threshold Correspondence (%) for CA and SA with Audiometric and Nonstandard Audiometric Headphones

	0–5 dB	10 dB	>15 dB
Comparisons including floor effect			
CA and SA with audiometric headphones	77	3.6	4.4
CA and SA with nonstandard audiometric headphones	78.4	3.8	4.9
Test–retest of CA	87.4	4.2	1.8
Test–retest of SA with audiometric headphones	86.6	3.8	3.9
Test–retest of SA with nonstandard audiometric headphones	78.7	2.6	2.5
Comparisons excluding floor effect			
CA and SA with audiometric headphones	70.2	12.7	15.1
CA and SA with nonstandard audiometric headphones	71.6	12.5	15.9
Test–retest of CA	81.1	12.2	6.8
Test–retest of SA with audiometric headphones	73.7	13	13.4
Test–retest of SA with nonstandard audiometric headphones	78.7	14.7	6.6

Table 3. Average Differences between CA and SA with Audiometric and Nonstandard Audiometric Headphones

	8 kHz	10 kHz	12.5 kHz	16 kHz
Average difference (SD; n)				
CA and SA with audiometric headphones	0.6 (6.7; 122)	1.3 (6.2; 120)	1.7 (8.6; 118)	1.2 (9.9; 118)
CA and SA with nonstandard audiometric headphones	−0.2 (4.2; 120)	3.2 (7.6; 121)	0.3 (5.1; 118)	−0.9 (8.1; 122)
Average difference (SD; n) excluding floor effect				
CA and SA with audiometric headphones	1 (11.1; 25)	1.5 (7.9; 27)	0.9 (8.6; 28)	0.1 (11; 43)
CA and SA with nonstandard audiometric headphones	0.2 (3.8; 27)	6.8 (8.6; 25)	0.9 (8.9; 34)	−2.2 (11; 52)
Average absolute difference (SD; n)				
CA and SA with audiometric headphones	3.0 (6.0; 122)	2.9 (5.6; 120)	3.3 (8.1; 118)	4.9 (8.6; 118)
CA and SA with nonstandard audiometric headphones	2.0 (3.6; 120)	3.5 (7.5; 121)	2.3 (4.6; 118)	4.5 (6.7; 122)
Average absolute difference (SD; n) excluding floor effect				
CA and SA with audiometric headphones	6.6 (8.9; 25)	5.6 (5.8; 27)	5.9 (6.2; 28)	7.8 (7.7; 43)
CA and SA with nonstandard audiometric	2.8 (2.5; 27)	8.0 (7.5; 25)	6.2 (6.4; 34)	8.2 (7.5; 52)

using nonstandard audiometric headphones, corresponded within 10 dB. This is almost identical to the test–retest correspondence with conventional EHF audiometry (93.3%). As EHF audiometry is typically used for monitoring purposes, the test–retest reliability is particularly important to ensure that early changes will be identified.

Previous studies on EHF audiometry reported similar test–retest correspondence. Frank (1990) and Frank and Dreisbach (1991) reported that close to 95% of test–retest EHF thresholds corresponded within 10 dB using Sennheiser HD 250 circumaural headphones. In a later study, using Sennheiser HDA 200 circumaural headphones, Frank (2001) reported between 95.4% and 100% of test–retest EHF thresholds within 10 dB difference. Schmuziger et al (2004) and Valente et al (1992) compared circumaural headphones with insert earphones. Schmuziger et al (2004) found test–retest correspondence to be similar between the Sennheiser HDA 200 circumaural headphones and Etymotic Research ER-2 insert earphones (ranging from 94% to 100%) correspondence within 10 dB. Valente et al (1992) reported 83–100% of EHF test–retest threshold correspondence within 10 dB, using Koss HV/1A+ headphones and 88–98% using ER-2 insert earphones. Although the results of these previous studies could be due to the cohorts and their hearing levels, results of the present study, using audiometric headphones, excluding the thresholds at 10 dB HL, are within the general range set by these previous studies.

The overall average absolute threshold differences, excluding thresholds at 10 dB HL, between conventional and smartphone EHF audiometry, using audiometric headphones (6.5 ± 7.2) and nonstandard audiometric headphones (6.2 ± 6.0), were within the range of the average absolute test–retest threshold differences, which were between 3.1 and 8.3. Previous studies, however, reported on average test–retest threshold differences, instead of average absolute test–retest threshold differences. Frank and Dreisbach (1991) found

Table 4. Average Test–Retest Reliability Differences for CA and SA with Audiometric and Nonstandard Audiometric Headphones

	8 kHz	10 kHz	12.5 kHz	16 kHz
Average difference (SD; n)				
Test–retest of CA	1.5 (3.7; 42)	0.1 (5.4; 42)	1 (3.2; 42)	0.7 (4.5; 42)
Test–retest of SA with audiometric headphones	0.6 (7.2; 40)	0.9 (6.1; 39)	0.4 (3.3; 39)	0.9 (6.9; 38)
Test–retest of SA with nonstandard audiometric headphones	0.0 (4.8; 40)	−1.0 (4.9; 38)	0.3 (5.1; 37)	3.4 (10.2; 40)
Average difference (SD; n) excluding floor effect				
Test–retest of CA	−1.4 (6; 11)	−0.5 (8.2; 11)	−0.8 (4.9; 13)	0.3 (5; 20)
Test–retest of SA with audiometric headphones	−1.7(12.3; 12)	−0.5 (11.4; 10)	−0.9 (6.3; 11)	−2.3 (7.5; 13)
Test–retest of SA with nonstandard audiometric headphones	−0.4 (5.6; 13)	3 (7.6; 5)	2.5 (4.6; 8)	−4.3 (7.3; 16)
Average absolute difference (SD; n)				
Test–retest of CA	1.1 (3.0; 42)	2.4 (4.5; 42)	1.1 (2.6; 42)	2.3 (3.5; 42)
Test–retest of SA with audiometric headphones	3.1 (6.5; 40)	2.4 (5.6; 39)	1.2 (3.1; 39)	2.2 (6.5; 38)
Test–retest of SA with nonstandard audiometric headphones	2.0 (4.4; 40)	2.6 (4.3; 38)	2.4 (4.5; 37)	5.1 (9.5; 40)
Average absolute difference (SD; n) excluding floor effect				
Test–retest of CA	3.2 (5.1; 11)	5.9 (5.4; 11)	3.1 (3.8; 13)	3.3 (3.7; 20)
Test–retest of SA with audiometric headphones	8.3 (8.9; 12)	6.5 (9.1; 10)	3.6 (5.0; 11)	3.1 (7.2; 13)
Test–retest of SA with nonstandard audiometric headphones	3.5 (4.3; 13)	7.0 (2.7; 5)	3.8 (3.5; 8)	5.6 (6.3; 16)

a ±1.1 dB average test–retest threshold difference, which was almost similar to that found by Valente et al (1992), reporting a 1.5 dB average test–retest difference, using Koss HV/1A+ headphones and a 1.3 dB average test–retest difference, using ER-2 insert earphones. Frank (1990), however, reported a very low 0.4 dB average test–retest difference. The average test–retest threshold differences of the present study, using both audiometric and nonstandard audiometric headphones, excluding thresholds at 10 dB HL, were similar to these studies, indicating good reproducibility.

The SD for the average test–retest threshold difference, excluding thresholds at 10 dB HL, was higher for smartphone EHF audiometry using audiometric headphones than for conventional EHF audiometry and smartphone EHF audiometry using nonstandard audiometric headphones. However, these results showed a higher variability than that of Frank (1990), and Frank and Dreisbach (1991), which ranged from 3.6 to 6.1 and 3.0 to 4.4, respectively. van Tonder et al (2017) reported similar variability (SDs), ranging from 3.9 to 4.7 for the average absolute differences between CA and SA across conventional frequencies (0.5, 1, 2, 4, and 8 kHz). The average absolute threshold difference of the present study showed almost similar variability, but still higher than that of van Tonder et al (2017). Although comparing pure tones and narrow band noise as test stimuli, John et al (2017) also found higher variability (4.2–15.2 SD) between pure-tone and a narrow-band noise signal in the EHF range, as opposed to 2.9–3.6 in the conventional frequency range.

The only significant difference between EHF threshold comparisons, between techniques (conventional versus smartphone) in the present study, was at 10 kHz, using nonstandard audiometric headphones ($p < 0.05$). This is likely due to the rapid decline in the frequency response found at 10 kHz, for this particular headphone, as reported by Van der Aerschot et al (2016), possibly causing variability at 10 kHz. These authors indicated that the nonstandard audiometric headphones, used in the present study, showed a flat frequency response across all frequencies except at 0.25, 4, and 10 kHz. A flat curve is preferred for audiometric testing; however, the nonstandard audiometric headphones showed notches at 4 and 10 kHz and a low, sloping frequency response at 0.25 kHz.

As all testing was conducted in a sound booth, application of SA with EHF outside a sound-treated environment has not been demonstrated. Smartphone testing for conventional frequencies outside of a sound booth, using real-time environmental noise monitoring, has previously been demonstrated to be reliable in certain settings (Sandström et al, 2016; Louw et al, 2017). The validity of EHF smartphone testing outside of a sound booth, as a cost-effective and readily available solution to detect high-frequency hearing loss in community-based primary healthcare settings in underserved areas, is important to establish.

A further limitation of this study was that SA only tested down to 10 dB HL. In 59.4% instances across all test frequencies for audiometric headphones, the participants' thresholds were at 10 dB HL, with both CA and SA. Direct threshold comparisons could, therefore, only be made on a subset of actual thresholds unaffected by a floor effect.

CONCLUSION

The present study demonstrates that accurate and reliable EHF thresholds can be determined by using a SA application on an Android platform, coupled with calibrated headphones. This may provide a mobile, affordable option for EHF audiometry in communities. For clinical use, this technology is available and may be acquired from the manufacturer. Persons receiving ototoxic medications, or exposed to loud noise levels, in particular those with limited access to these hearing healthcare services in particular, may benefit with this type of technology.

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