Validation of hearTest Smartphone Application of Extended High Frequency Hearing Thresholds

By

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Table of Contents

TABLES

FIGURES

LIST OF ABBREVIATIONS

EHF: Extended high-frequencies

kHz: Kilohertz

dB: Decibel(s)

HL: Hearing level

mHealth: Mobile health

OS: Operating system

SD: Standard deviation

GBD: Global Burden of Disease

YLDs: Years lived with disability

NIHL: Noise-induced hearing loss

dB (A): A-weighted decibel

HIV: Human immunodeficiency virus

ART: Antiretroviral therapies

ENT: Ear, nose and throat

MDR-TB: Multi-drug-resistant tuberculosis

XDR-TB: Extensive drug-resistant tuberculosis

DPOAE: Distortion product oto-acoustic emissions

PC: Personal computer

ETSPL's: Equivalent threshold sound pressure levels

App: Application

NBN: Narrow band noise

FORMATTING

APA 6th edition manuscript format and referencing style was utilised in this dissertation.

Abstract

Extended high frequency audiometry is particularly valuable in a number of clinical areas, such as ototoxicity monitoring, and may relate to speech recognition and localisation. Accurate and reliable extended high frequency testing, with smartphone technologies, has the potential to provide more affordable and widely available access in underserved contexts. The aim of the current study was to determine the accuracy and test-retest reliability of extended high frequency audiometry with a smartphone application, using calibrated headphones.

Air conduction thresholds (8 – 16 kHz) and test-retest reproducibility recorded with conventional and smartphone audiometry, using standard audiometric (Sennheiser HDA 300) and non-standard audiometric headphones (Sennheiser HD202 II), was compared in a repeated-measures design. A total of 61 participants (122 ears) were included in the final analysis. Of these, 24 were adults with known exposure to ototoxic medications (mean age 36.8, SD 14.2 years; age range 22 – 64 years; 48% female), and 37 were adolescents (mean age 17.6, SD 3.2 years; age range 16 – 23 years; 76% female). Threshold comparisons were made between conventional audiometry and smartphone-based audiometry, with standard audiometric headphones and non-standard 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.

Conventional and smartphone thresholds corresponded at the lowest intensity (10 dB HL), using standard audiometric and non-standard 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 standard audiometric

headphones, and 84.1% of cases using non-standard audiometric headphones. There was no significant difference between conventional and smartphone audiometry using standard 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 standard and non-standard audiometric headphones, respectively.

Extended high-frequency smartphone audiometry, with calibrated headphones, can provide an accurate and reliable option for affordable mobile audiometry. This type of technology may especially benefit those individuals receiving ototoxic medication in areas where diagnostic equipment, such as an audiometer with extended high frequency testing capabilities in a sound booth, are inaccessible.

Keywords: extended high frequencies, automated audiometry, threshold audiometry, air conduction, mHealth, smartphone, validation, ototoxicity, noise-induced hearing loss, ageing

1. Introduction

The Global Burden of Disease (GBD) study 2015 indicated that 1.23 billion people lived with some form of hearing loss (Vos et al., 2015). The results showed that hearing loss has moved from the 11th leading cause of years lived with disability (YLDs) in 2010, to the 4th leading cause in 2015 (Vos et al., 2012; Vos et al., 2015; Vos et al., 2016; Wilson, Tucci, Merson, & O'Donoghue, 2017). More specifically, the prevalence of a disabling hearing loss, in both children and adults were thought to be higher in developing regions, such as the Asian Pacific area, southern Asia and sub-Saharan Africa (Mulwafu, Ensink, Kuper, & Fagan, 2017; Olusanya, Neumann, & Saunders, 2014; Stevens et al., 2011). Hearing loss will become even more prevalent as the average life expectancies increase globally (Mulwafu et al., 2015; Olusanya et al., 2014). Apart from age-related hearing loss, other contributing factors include hearing loss due to exposure to noise and ototoxic medications (Arslan, Orzan, & Santarelli, 1999; Basner et al., 2014; Fuente & Hickson, 2011; Olusanya et al., 2014).

Noise-induced hearing loss (NIHL) remains a leading cause of sensorineural hearing loss in occupational settings (Basner et al., 2014; Mehrparvar et al., 2014; Mehrparvar, Mirmohammadi, Ghoreyshi, Mollasadeghi, & Loukzadeh, 2011; Nelson, Nelson, Concha-Barrientos, & Fingerhut, 2005; Olusanya et al., 2014; Palmer et al., 2002; WHO, 2015). However, the rapid urbanisation in many emerging economies, together with the lack of enforceable regulations on environmental and occupational noise, further adds to this prevalence (Basner et al., 2014; Olusanya et al., 2014).

Apart from occupational and environmental noise exposure, there has also been a growing concern regarding unsafe noise levels in non-occupational settings, such as social and leisure-related noise (Serra et al., 2005). Earlier studies, measuring the sound levels in nightclubs,

found average sound levels between 93.2 and 109.7 dB (A) (Bray, Szymanski, & Mills, 2004; Potier et al., 2009; Santos et al., 2007). This far surpasses the sound levels considered dangerous in occupational settings. In occupational settings, sound levels greater than 80 dB to 85 dB (A), for more than 8 hours a day, without auditory protection, are considered dangerous (Dehnert et al., 2015; Occupational Health and Safety Act, 2003; Potier et al., 2009). More recent studies have investigated the risks associated with loud sounds, not only in night clubs, but in various other leisure settings, e.g. at pubs, bars, fitness classes, live sporting events, concerts, live music venues, and movie theatres (Beach, Gilliver, & Williams, 2013; Beach, Williams, & Gilliver, 2013; Huth, Popelka, & Blevins, 2014; Twardella et al., 2016). Nightclubs remain the most high-risk leisure noise, however these studies also found that the more leisure-related noise participants were exposed to, the more tinnitus and perceived risks of hearing damage were reported (Beach, Gilliver, et al., 2013; Beach, Williams, et al., 2013). Another study estimated the total leisure-related noise exposure, as well as the association with hearing loss among adolescents (Dehnert et al., 2015). These authors found that approximately 42% of adolescents were possibly exposed to dangerous levels of leisure-related noise. Although they did not find an association between audiometric findings and continuous noise exposure, they did find an association with impulse noise exposure.

Another important cause of hearing loss is through the use of ototoxic medications used to treat neonatal infections, malaria, cancer, human immunodeficiency virus (HIV) infection, and tuberculosis (Durrant et al., 2009; Harris et al., 2012; Mulwafu et al., 2015; Olusanya et al., 2014). It is thought that HIV and tuberculosis will become more prevalent in certain areas, such as Africa and Asia, due to the increasing resistance of these conditions, and the increasing availability of antiretroviral therapies (ART) and other treatments, therefore

associated hearing loss is likely to increase, as a result (Christopher, Edward, Sabrina, & Agnes, 2013; Dheda et al., 2017; Mulwafu et al., 2015; Tshifularo, Govender, & Monama, 2013). It is further estimated that 70% of cancers, including those related to ear, nose, and throat (ENT), will occur in developing regions by the year 2030 (Farmer et al., 2010; Mulwafu et al., 2015). The combination of exposure to ototoxic medications and noise exposure, either occupational or leisure-related, may have further compounding effects on hearing sensitivity (Davis et al., 2016; Langer, am Zehnhoff-Dinnesen, Radtke, Meitert, & Zolk, 2013).

Age-related hearing loss, NIHL, and ototoxicity are characterised by an initial presentation in the high frequencies that gradually progresses towards the lower frequencies. The gradual change in hearing sensitivity may, initially, go unnoticed, as speech perception is dominated by low-frequency hearing (Vlaming et al., 2014). However, the extended high frequencies (EHF) play an important role in speech perception, especially in the presence of background noise, and may, therefore, underpin everyday listening difficulties (Rodriguez Valiente, Garcia Berrocal, Roldan Fidalgo, Trinidad, & Ramirez Camacho, 2014; Vitela, Monson, & Lotto, 2014; Vlaming, MacKinnon, Jansens, & Moore, 2014). This, coupled with the slow progression of hearing loss, means that individuals often wait too long to seek help and that the hearing loss goes undetected, despite presenting with communication difficulties in certain situations (Vlaming et al., 2014). Early detection can, therefore, be beneficial in providing monitoring and early intervention. This may be accomplished by monitoring hearing sensitivity at the highest audible frequencies (9 – 20 kHz), before hearing loss progresses towards the lower conventional frequencies (0.125 – 8 kHz) relevant for speech understanding (Durrant et al., 2009; Gordon, Phillips, Helt, Konrad-Martin, & Fausti, 2005; Harris, Peer, & Fagan, 2012; Jacobs et al., 2012; Rodriguez Valiente et al., 2014; Vlaming et

al., 2014).

EHF audiometry is well established as an early detection tool for possible ototoxic hearing loss, as it alerts the physician of early ototoxic effects and could possibly motivate the change of the course of treatment (Arora et al., 2009; Fausti et al., 1992; Fausti et al., 1994; Gordon et al., 2005; Knight, Kraemer, Winter, & Neuwelt, 2007; Northern, Downs, Rudmose, Glorig, & Fletcher, 1972; Vasquez & Mattucci, 2003; Rodriguez Valiente et al., 2014). There has also been a growing interest in including EHF audiometry in hearing conservation programs (Balatsouras, Homsioglou & Danielidis, 2005; Liberman, Epstein, Cleveland, Wang, & Maison, 2016; Macca et al., 2015; Mehrparvar et al., 2014; Mehrparvar et al., 2011; Somma et al., 2008; Vlaming et al., 2014). Both ototoxic monitoring and hearing conservation programs aim to detect changes in the cochlea as early as possible, although no definite conclusions regarding the effect of noise exposure on EHF thresholds exist (Liberman et al., 2016; Schmuziger, Patscheke, & Probst, 2007; Vlaming et al., 2014). Following acoustic trauma, some authors found a threshold shift at 3 – 6 kHz with a considerable hearing loss in the EHF range, especially at 14 and 16 kHz (Dieroff, 1982; Macca et al., 2014; Mehrparvar et al., 2014; Mehrparvar et al., 2011; Somma et al., 2008). Another study found that EHF audiometry was more sensitive than conventional audiometry 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. In contrast, other studies found EHF provided no significant additional information at 9 – 14 kHz, for early detection of NIHL (Balatsouras et al., 2005; Osterhammel & Osterhammel, 1979; Schmuziger et al., 2007).

Recent studies have further investigated early neural degeneration in ageing and noise-

exposed ears (Hickox, Larsen, Heinz, Shinobu, & Whitton, 2017; Kobel, Le Prell, Liu, Hawks, & Bao, 2016; Liberman et al., 2016; Liberman & Kujawa, 2017; Liberman & Liberman, 2015). These authors suggest that hair cells are, in fact, not the most vulnerable component in the inner ear, but instead that the synapses between the hair cells and cochlear nerve terminals are. Although this loss of synapses is immediate, cochlear synaptopathy may remain "hidden" on behavioural or electrophysiological testing, until it becomes severe (Liberman et al., 2016; Liberman & Kiang, 1978; Lobarinas, Salvi, & Ding, 2013). They found that behavioural testing, such as the conventional pure tone audiogram and distortion product oto-acoustic emissions (DPOAE), might not be sensitive enough in detecting cochlear synaptopathy (Hickox et al., 2017; Kobel et al., 2016; Liberman et al., 2016; Liberman & Kujawa, 2017). Several authors have further suggested that this may contribute to the difficulty in understanding speech while in noisy listening environments, as well as tinnitus and hyperacusis (Hickox & Liberman, 2014; Knipper, Van Dijk, Nunes, Ruttiger, & Zimmerman, 2013; Kujawa & Liberman, 2015; Liberman et al., 2016; Plack, Barker, & Prendergastt, 2014; Roberts et al., 2010; Schaette, 2014; Schaette & McAlpine, 2011). Liberman et al. (2016), therefore, aimed at diagnosing a possible cochlear synaptopathy in humans by assessing DPOAE's, click-evoked electrocochleography, behavioural audiometry, and word recognition with or without noise in college students. In the high-risk group for cochlear synaptopathy, they found significant threshold elevations between 10 and 16 kHz in EHF behavioural audiometry, significant difference in ratio between the waveform peaks generated by hair cells (i.e. the summating potential) and the cochlear neurons (i.e. the action potential) in electrocochleography, as well as significantly poorer word recognition in noise. They concluded that a combination of these tests could possibly allow for early detection where standard audiometry would not.

Considering what has been mentioned on page 14, 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 (Rodriguez Valiente et al., 2014). However, these audiometers are usually only found in private or tertiary health care facilities, and are not widely accessible to at-risk patients in rural settings and low- and middle-income countries (Swanepoel et al., 2010; Swanepoel & Hall, 2010; Swanepoel, Koekemoer, & Clark, 2010). Ideally, monitoring of hearing thresholds at the EHF range for at-risk patients should be provided for at primary health care levels, or even in the homes of individuals (Balatsouras et al., 2005). 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 multi-drug-resistant tuberculosis (MDR-TB) patients, or patients receiving chemotherapy.

Whilst 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 (Eikelboom, Swanepoel, Motakef, & Upson, 2013; Swanepoel & Biagio, 2011; Swanepoel et al., 2010; Swanepoel, Maclennan-Smith, & Hall, 2013; Swanepoel, Matthysen, Eikelboom, Clark, & Hall, 2015; Swanepoel, Mngemane, Molemong, Mkwanazi, & Tutshini, 2010). Several studies, including a systematic review and meta-analysis, have compared automated and conventional audiometry methods, and have shown clinical validity (Mahomed, Eikelboom, & Soer, 2013; Sandstrom, Swanepoel, Myburgh, & Laurent, 2016; Swanepoel & Biagio, 2011; Swanepoel et al., 2010; Van Tonder, Swanepoel, Mahomed-Asmail, Myburgh, & Eikelboom, 2017). These studies, however, have been limited to

conventional audiometric frequencies (0.5 – 8 kHz). Helt (2013) and Jacobs et al. (2012) investigated the effectiveness of a portable, PC-based system for detecting and monitoring ototoxicity. The device has both audiologist-directed (manual) and patient self-test (automated) capabilities. The automated (patient self-test) testing, across conventional and extended high frequencies (0.5–20 kHz), was comparable to conventional audiometry.

Smartphone audiometry solutions have, recently, been proposed as a way to dramatically reduce cost and increase access whilst integrating environmental sensors, data capturing and uploading capabilities (Clark & Swanepoel, 2014; Swanepoel, Myburgh, Howe, Mahomed, & Eikelboom, 2014). Recent studies have already demonstrated real promise for the use of smartphone applications for hearing assessment in different populations (Mahomed-Asmail, Eikelboom, Myburgh, & Hall, 2016; Sandstrom et al., 2016; Swanepoel et al., 2014; Van Tonder et al., 2017), and validated the use of non-audiometric supra-aural headphones, with established equivalent threshold sound pressure levels (ETSPL's) as a cost-effective alternative for hearing screening (Van der Aerschot, Swanepoel, Mahomed-Asmail, Myburgh, & Eikelboom, 2017).

Studies on an Android smartphone application (hearScreen™) demonstrated that a low-cost smartphone, with calibrated headphones, produced clinical results comparable to conventional school-based screening (Mahomed-Asmail et al., 2016; Swanepoel et al., 2014). Its use in primary healthcare settings (Louw, Eikelboom, & Myburgh, 2017) and community-based screening programs, using minimally trained persons (Yousuf Hussein et al., 2016) has also been demonstrated. Further studies, using the technology to determine hearing thresholds, have indicated that accurate thresholds could be determined using this technology in conventional clinical settings, and at primary health care settings (Sandstrom et al., 2016;

Van Tonder et al., 2017). The clinical validity of the use of smartphone audiometry for extended high frequencies has not been demonstrated, however. This type of smartphone technology that allows for accurate EHF testing can provide EHF screening and monitoring in specific populations, where diagnostic equipment, such as an audiometer with EHF testing capabilities in a sound booth, are inaccessible. The aim of this study was to determine the accuracy and reliability of smartphone audiometry with calibrated headphones, for determining EHF thresholds.

The following question therefore arises: *Can the hearTest smartphone application provide valid, extended high-frequency thresholds compared to conventional audiometry?*

2. Methodology

2.1 Aim and Objectives

2.1.1 Aim

To determine the validity of a smartphone-based application (hearTest) for extended high frequencies (EHF), using calibrated headphones.

2.1.2 Objectives

1. To describe and compare the accuracy of EHF air conduction thresholds, determined with conventional and smartphone-based audiometry, using standard audiometric headphones and non-standard audiometric headphones.

2. To determine test-retest reliability of EHF air conduction thresholds, determined with conventional and smartphone-based audiometry, using standard audiometric headphones and non-standard audiometric headphones.

2.2 Research Design

A repeated-measures design (Leedy & Ormrod, 2013) was used to compare hearing thresholds (dependent variable) within participants across the different test conditions (independent variable). All participants were tested in the following test conditions: i) conventional EHF audiometry with standard audiometric headphones, ii) smartphone EHF audiometry with standard audiometric headphones, iii) smartphone EHF audiometry with non-standard audiometric headphones, iv) Participants underwent a fourth repeated measurement of any one of the three test conditions to determine test-retest reliability.

Counterbalancing was used in an effort to ensure that an equal number of tests were conducted on all participants and that the results were not influenced by the test order.

2.3. Ethical Considerations

Ethical guidelines serve as the standard and basis on which research is conducted (Strydom, 2012). Ethical clearance to conduct the study was granted from the University of Pretoria's Faculty of Humanities' Research Proposal and Ethics Committee, prior to data collection (Appendix A). Permission from Dr George Mukhari Academic Hospital, as well as the Speech Therapy and Audiology Department at Dr George Mukhari Academic Hospital, was attained before the selection and contact of subjects (Appendix B).

To ensure that the study was carried out in an ethical manner, the Guidelines for the Responsible Conduct of Research: Ethics and the Publication Process (ASHA, 2009) were used. As the guidelines are relevant to this study, they were specifically adhered to.

Protecting human participants in research. It is an ethical obligation to protect the participants from any form of physical discomfort or emotional harm that may emerge from the research project (Strydom, 2012). The letter of consent (Appendix C & D) stipulated the requirements of participating in the research project. It indicated that participation in the research is voluntary, and that it can be terminated at any point in time.

Informed consent. Consent was obtained from all of the participants. The ethical principle of informed consent specifies that the participants and significant others should be informed regarding the nature of the study conducted and be given the choice of either participating or not participating (Leedy & Ormrod, 2013). The letter of informed consent (Appendix C & D) was given to each participant. The letter contains a complete and well-defined explanation of the procedures, in which the participants will partake.

Data management. Data management ensures that data is confidential, secure, accurately recorded, and trustworthy (ASHA, 2009). Confidentiality was ensured by removing any element that may reveal the participants' identities (Babbie & Mouton, 2012). The personal identities of participants were kept confidential by assigning a numerical code to each participant. Only these numerical codes were mentioned in the results.

Data retention. The data will be stored for 15 years, both in hard copy and in electronic format at the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

Manuscript preparation. The final product is accurate and complete. It includes the following sections as per ASHA (2009) guidelines: title and abstract; review of literature; selection of methodologies; report of results and discussion.

2.4 Participants

2.4.1 Population and Sampling

Male, female, adolescent and adult participants, with a range of hearing sensitivities, were sampled. Participants were selected by using a non-probability, purposive sampling method (Strydom, 2012). Participants with the most characteristic and representative attributes of the population, that served the purpose of the study, were sampled. A prospective power analysis indicated that a minimum of 30 subjects is required for detecting a medium sized effect when employing the traditional .05 criterion of statistical significance. A total of 60 participants were included in the study. Twenty-three were recruited from the Speech Therapy and Audiology Department at Dr George Mukhari Hospital (Group 1: mean age 36.8, SD 14.2 years; age range 22-64 years; 48% female). Of these, 41.6 % had history of receiving potentially ototoxic medication and 26.1 % already presented some degree of hearing loss. The remaining 37 participants were recruited from the University of Pretoria's prospective students programme (Group 2: mean age 17.6, SD 3.2 years; age range 16-34 years; 76% female).

2.4.2 Selection Criteria

A selection criterion was determined to select appropriate participants that comply with the requirements of the study. This selection criterion is described in Table 1.

Table 1

Selection criteria of elements essential for eligibility to be included in the current study

Inclusive criteria	Motivation
Subjects between the ages of 13 years and 65 years	The purpose of the study is to determine the accuracy and validity of smartphone audiometry in adolescents, young adults, and adults. Although the age limits differ for adolescence, the beginning stage starts between 11 and 13 years, and ends between 17

	and 21 years (Louw & Louw, 2007). The World Health Organization (WHO) defines adolescents as those individuals between 10 and 19 years of age (World Health Organization, n.d., para. 1). According to the Children's Act of South Africa, adolescence ends at the age of 18 years (Children's Act 38, 2005). Therefore, persons from the age of 18 years and older are considered as adults (Louw & Louw, 2009). Elderly individuals may present decreased memory or attention, which may negatively impact performance on the test measurements (Hällgren, Larsby, Lyxell, & Arlinger, 2001).
Male and female	As far as possible, an even gender distribution was selected to ensure a representative sample.
Normal middle ear function	Any middle ear abnormality may affect the conduction of sound, resulting in a decreased hearing sensitivity (Hall & Mueller, 1997). Normal middle ear function was determined by an otoscopic evaluation and tympanometry.
Subjects with a range of hearing sensitivity.	Participants with normal hearing as well as a hearing loss (excluding an asymmetrical hearing loss, or conductive hearing loss with an air-bone gap greater than 10 dB) were selected to be able to generalise findings and ensure a representative sample. Hearing sensitivity was determined by conventional pure tone audiometry.

2.5 Research Apparatus

The collection of data for the study includes apparatus, materials, and settings for the collection of quantitative data.

The apparatus used in the study included an otoscope, tympanometer, audiometer, smartphone, standard audiometric headphones, and non-standard audiometric headphones, as indicated in Table 2. 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 tympanometery was unavailable.

Table 2

Description of research apparatus

Apparatus	Description
Otoscope	With Group 1, a wall-mounted Welch-Allyn otoscope was used to determine any abnormality of the tympanic membrane and ear canal as well as the possibility of ear canal collapse (Hall & Mueller, 1997). A Welch-Allyn MacroView otoscope was used for Group 2.
Tympanometer	A diagnostic tympanometer (GSI Tympstar) was used to determine the middle ear status, and to ensure that no middle ear involvement would influence pure tone testing.
Audiometer	A diagnostic two-channel audiometer (GSI 61 Clinical Audiometer) with extended high frequencies was used for determining pure tone thresholds for conventional and extended high frequencies.
Smartphone	The Samsung Galaxy Trend Neo smartphone, using Android as operating

		system, was used for determining extended high frequencies. The smartphone has a physical size of 3.50 inches and a resolution of 320 x 480 pixels, powered by a single core, 850 MHz processor.
Standard headphones	**audiometric**	For the conventional high frequency audiometry, acoustic stimuli was presented through the Sennheiser HDA 200 circumaural headphones. For the smartphone audiometry, acoustic stimuli was presented through the Sennheiser HDA 300 circumaural headphones.
Non-standard headphones	**audiometric**	Acoustic stimuli was presented through the Sennheiser HD202 headphones.

Materials used were the hearTest ® application on Android OS version 4.0.4, that allow for automated threshold determination at conventional and extended high frequency ranges.

Thresholds determined with conventional and smartphone audiometry were recorded on a dedicated recording sheet for each participant (*Appendix E*).

2.6 Research Procedures

Procedures include data collection, data processing, and data analysis.

2.6.1 Data Collection

Data was collected in a cross-sectional manner. Extended high frequencies (8, 12.5, 14, and 16 kHz) were determined across the test conditions described in Table 3 for each participant. Data was collected on the same day for each participant. Test order was counterbalanced to control any order of effect, and to maintain internal validity (Leedy & Ormrod, 2013). Data collection commenced after the study has been deemed ethically responsible and practically feasible by the appropriate institutions.

Table 3

Description of test conditions

Test condition	Description
1. Conventional	Pure tone air conduction thresholds were determined for 8, 12.5, 14, and 16 kHz in

audiometry with standard audiometric headphones in a sound booth	each ear for all participants, using a conventional high frequency audiometer. Participants were expected to respond to the pure tone signal by pressing a response button. The modified Hughson-Westlake method (Carhart & Jerger, 1959) for determining pure tone thresholds was used. Standard audiometric headphones were used as transducers.
2. Smartphone audiometry with standard audiometric headphones in a sound booth	Pure tone air conduction thresholds were determined for 8, 12.5, 14, and 16 kHz in each ear for all participants, using smartphone audiometry. Participants were expected to respond to the automated pure tone signal by pressing a virtual response button on the smartphone screen. Standard audiometric headphones were used as transducers.
3. Smartphone audiometry with non-standard audiometric headphones in a sound booth	Pure tone air conduction thresholds were determined for 8, 12.5, 14, and 16 kHz in each ear for all participants using smartphone audiometry. Participants were expected to respond to the automated pure tone signal, by pressing a virtual response button on the smartphone screen. Non-standard audiometric headphones were used as transducers.
4. Repeated Test condition 1, 2, or 3.	Each participant was divided into subgroups to perform a repeated measure of either one of the three test conditions.

2.6.2 Data Processing and Analysis

Microsoft Excel, version 14.3.6 for Mac 2011, was used to enter and store the data. The data was, therefore, entered on an Excel spreadsheet, whereby each participant corresponded to a row and each variable to a column (Kruger, de Vos, Fouche, & Venter, 2005). Each participant was assigned a numerical code to maintain confidentiality.

Data was analysed quantitatively and described before interpretations were made regarding the meaning of the data (Kruger et al., 2005). Data was, therefore, analysed using Microsoft Excel (Microsoft Inc, Redmond, WA, USA) and IBM SPSS Statistics software programme (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp.), to determine if the automated threshold determination was as accurate and reliable.

Any form of measurement typically falls into one of four categories, or levels: nominal, ordinal, interval, or ratio (Leedy & Ormrod, 2013). The level of measurement determines the statistical procedures that can be used to process data. Hearing sensitivity is measured in dB HL and has an arbitrarily established zero point (Martin & Clark, 2010), meaning hearing

sensitivity can be measured even below zero dB. An interval scale of measurement was, therefore, used to determine the mean, standard deviation, and Pearson product moment correlation (Leedy & Ormrod, 2013). Furthermore, it allowed for descriptive statistical analysis (Leedy & Ormrod, 2013).

Data was normally distributed (Shapiro-Wilk Test of Normality), therefore parametric analysis (paired sample t Test) was used to determine if any significant differences between conventional and smartphone audiometry exist ($p>0.05$). The Bonferroni correction was applied to maintain a statistical probability of $p<0.05$ as significant. Measures of central tendency (mean) and variability (standard deviation, range) were used to describe statistically significant differences between conventional and smartphone audiometry. Data was represented by means of tables so as to ensure that all results were clearly defined and did not misrepresent the findings of the study (Leedy & Ormrod, 2013).

2.7 Reliability, Validity, and Trustworthiness

Accountability measurements were included to ensure the trustworthiness of the study, as well as the data obtained.

2.7.1 Reliability

Reliability is the consistency of measurements when replicated with the same variables (Leedy & Ormrod, 2013). With the goal of using reliable measurements that yield consistent results, the following was done:

- The test measurements were administered in a consistent manner by a trained audiologist.

- The test order was counterbalanced so as to maintain internal validity. However, consistent and accurate instructions were given to the participants.
- An established procedure for pure tone audiometry, the modified Hughson-Westlake method (Carhart & Jerger, 1959), was used to determine thresholds for the conventional audiometry.
- Test-measurements were repeated to determine test-retest reliability.

2.7.2 Validity

Validity refers to the extent to which a measurement instrument will measure what it is intended to measure (Delport & Roestenburg, 2012). There are four categories of validity, as discussed by Delport and Roestenburg (2012): content validity, face validity, criterion validity, and construct validity.

Content validity. Content validity refers to the representativeness of the content of an instrument (Delport & Roestenburg, 2012). It therefore focuses on whether the full content of the concept being measured is represented. With regards to the study, this refers to the measurements being an accurate representation of the participants' hearing sensitivity in higher frequencies. The instrumentation chosen for this study have been developed to measure hearing sensitivity in conventional and high frequency audiometry.

Face validity. Face validity refers to the apparent appearance or face value of a measurement procedure (Delport & Roestenburg, 2012). In this study, there was high face validity for the measurements, as the measuring instruments are calibrated and the pure tone threshold test included in the study, form part of the standard test battery for hearing assessment.

Criterion validity. Criterion validity is the extent to which the results of a measuring instrument correlates with another related measurement (Leedy & Ormrod, 2013). For this study, measurements from the smartphone audiometry were compared with the conventional audiometry to determine its criterion validity.

Construct validity. Construct validity is concerned with the meaning of the measurement procedure, and whether the test or procedure assessed the theory that is being investigated (Delport & Roestenburg, 2012). For this study, there was adequate construct validity, as the materials selected are appropriate to test the hypothesis.

3. Extended High Frequency Smartphone Audiometry: Validity and Reliability

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3.1 Abstract

Background**:** Extended high frequency audiometry (8 – 16 kHz) has an important role in audiological assessments such as ototoxicity monitoring, and for speech recognition and localisation. Accurate and reliable extended high frequency 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 extended high frequency audiometry with a smartphone application, using calibrated headphones.

Research Design: Air conduction thresholds (8 – 16 kHz) and test-retest reproducibility, recorded with conventional and smartphone audiometry, using audiometric (Sennheiser HDA 300 circumaural) and non-standard 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 TB clinic (mean age 36.8, SD 14.2 years; 48% female), and 37 were adolescents and young adults recruited from a prospective students programme (mean age 17.6, SD 3.2 years; 76% female). Of these, 22.3% (n= 326) of EHF thresholds were ≥ 25 dB HL.

Data Analysis: Threshold comparisons were made between conventional audiometry and smartphone-based audiometry, with audiometric headphones and non-standard 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 non-standard 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 non-standard audiometric headphones. There was no significant difference between conventional and smartphone audiometry, 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 non-standard audiometric headphones, respectively.

Conclusion: Extended high frequency 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.

Keywords: extended high frequencies, automated audiometry, diagnostic audiometry, mHealth, smartphone, ototoxicity, noise-induced hearing loss, ageing

Acronyms and abbreviations: EHF = extended high frequencies; mHealth = mobile health; OS = operating system; SD = standard deviation

3.2 Introduction

The Global Burden of Disease (GBD) 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 (YLDs) in 2010, to the 4th leading cause in 2015 (Vos et al, 2012; Vos et al, 2015; Vos et al, 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 above 65 years 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 urbanisation 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 non-occupational settings, such as social and environmental noise (Serra et al, 2005). The WHO (2015) estimates that 1.1 billion teenagers and young adults are at risk for developing a hearing loss, due to unsafe use of personal audio devices and due to recreational events, such as night clubs and sport events.

Not only can excessive noise damage hearing, but so too can medications used to treat neonatal infections, malaria, cancer, human immunodeficiency virus (HIV) infection, and tuberculosis cause auditory and/or vestibular dysfunction, that may lead to a permanent hearing loss (Durrant et al, 2009; Harris et al, 2012; Olusanya et al, 2014; Mulwafu et al, 2015). 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, and ototoxicity may be observed as a high frequency hearing loss that gradually progresses towards lower frequencies (Durrant et al, 2009; Seddon et al, 2012; Mehrparvar et al, 2014). The acoustic energy of extended high frequencies (EHF) plays an important role in speech perception, especially in the presence of background noise (Rodriguez 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 towards the conventional audiometric frequencies (0.125 – 8 kHz) most relevant for speech understanding (Gordon et al, 2005; Durrant, 2009; Harris et al, 2012; Jacobs et al, 2012; Rodriguez 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; Macca et al, 2014; Mehrparvar et al, 2014; Vlaming et al, 2014; 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 to 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; Macca et al, 2014; Mehrparvar et al, 2014). Another study found that EHF audiometry was more sensitive than conventional audiometry 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. In contrast, other studies found EHF provided no significant additional information at 9 to 14 kHz for early detection of NIHL (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 EHF's (Rodriguez Valiente et al, 2014). However, these audiometers are usually only found in private or tertiary health care facilities, and are not widely accessible to at-risk patients in rural settings (Swanepoel et al, 2010b; Swanepoel et al, 2010c). Ideally, monitoring of hearing thresholds at the EHF range for at-risk patients should be provided at primary health care 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 multi-drug resistant tuberculosis patients, or patients receiving chemotherapy.

Whilst 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 et al, 2010a; Swanepoel et al, 2010b, Swanepoel et al, 2010c; Swanepoel and Biagio, 2011; Eikelboom et al, 2013). Several studies, including a systematic review and meta-analysis, have compared automated and conventional audiometry methods, and have shown clinical validity (Swanepoel and Biagio, 2011; Mahomed et al, 2013; Sandstrom 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 extended high frequencies (0.5–20 kHz) was comparable to conventional audiometry.

Smartphone audiometry solutions have been proposed as a way to reduce cost and increase access, whilst 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; Sandstrom et al, 2016; Van Tonder et al, 2017), and validated the use of non-audiometric supra-aural headphones with established equivalent threshold sound-pressure levels (ETSPL's) as a cost-effective alternative for hearing screening (Van der Aerschot et al, 2017).

Studies on an Android smartphone application (hearScreen^{TM}) demonstrated that a low-cost smartphone with calibrated headphones produced clinical results comparable to 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 (Youssuf 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 health care settings (Sandstrom et al, 2016; Van Tonder et al, 2017). Clinical validity of smartphone audiometry 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 smartphone audiometry with audiometric headphones, as well as non-standard audiometric headphones as a possible low-cost solution, for determining EHF thresholds.

3.3 Method

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 prior to any data collection. A repeated-measures within-subject design (Leedy and Ormrod, 2014) was used to compare hearing thresholds determined by smartphone and conventional EHF audiometry. All participants were tested in the following test conditions: i. Conventional EHF audiometry, with audiometric headphones; ii. Smartphone application, with audiometric headphones; iii. Smartphone application, with calibrated, non-standard audiometric headphones; iv. Participants underwent a fourth repeated measurement of either one of the three test conditions to determine test-retest reliability.

3.3.1 Subjects

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, SD 14.2 years; age range 22 – 64 years; 48% female). Of these twenty-four 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 years; age range 16 – 23 years; 76% female). The selection criterion specified the inclusion of hearing sensitivity, i.e. 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.

3.3.2 Equipment and Procedures

All hearing threshold measurements were conducted in a sound booth. A diagnostic two-channel audiometer (GSI 61 Clinical Audiometer), with circumaural Sennheiser HDA 200 headphones, was used for the conventional EHF audiometry condition. Audiometric testing equipment was calibrated on 05/12/2014 and according to the South African Bureau of Standards (SANS 10154-1; 10154-2) based on the 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 OS (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, 2015; Mahommed-Asmail et al, 2016; Sandstrom et al, 2016; Louw et al, 2017), that 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 IEC 60318-1 G.R.A.S. Ear simulator 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 ETSPL's by van der Aerschot et al (2016), were used for the non-standard audiometric headphone condition.

Data was 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 conventional audiometry condition was conducted by an audiologist (1st author). However, the test operator did not view the results prior to 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 Hughson-Westlake method (Carhart and Jerger, 1959) by pressing a virtual response button on the touchscreen of the smartphone.

3.3.3 Analysis

Smartphone testing had certain intensity limitations, as opposed to conventional audiometry. In 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 smartphone audiometry was 10 dB HL, conventional audiometry was limited to test to the same level. To account for a possible floor affect, conventional and smartphone thresholds that were at 10 dB HL, as well as exceeded 10 dB HL, were compared.

Data was recorded and analysed using Microsoft Excel and SPSS (IBM Corp. Released 2013. IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY: IBM Corp.). Threshold data for conventional audiometry and smartphone audiometry (>10 dB HL) was analysed

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.

3.4 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, nor for conventional EHF audiometry. These instances were excluded from 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 non-standard audiometric headphones.

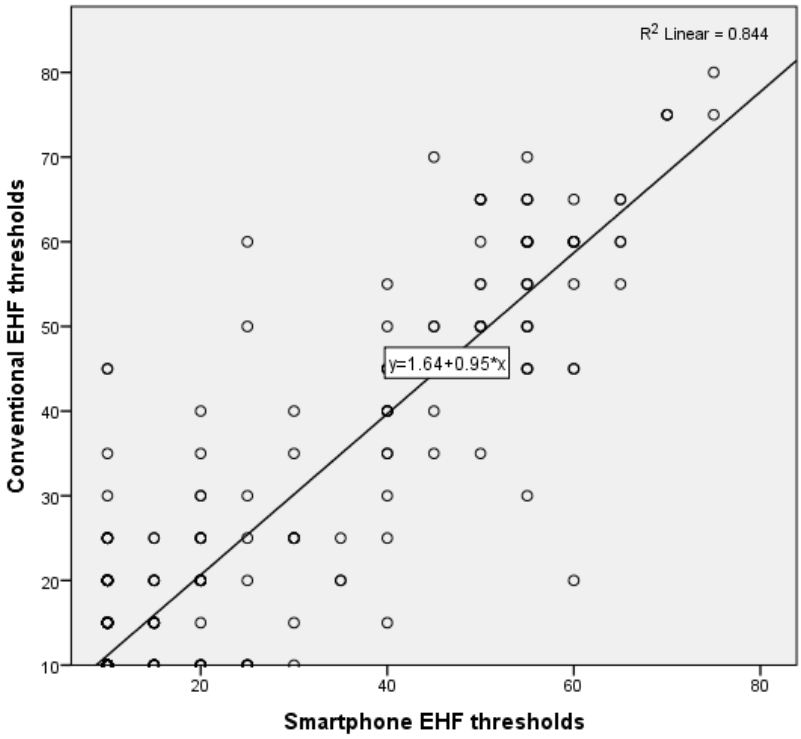

Figure 1. The relationship of thresholds (dB HL) determined with conventional EHF audiometry and smartphone EHF audiometry using audiometric headphones.

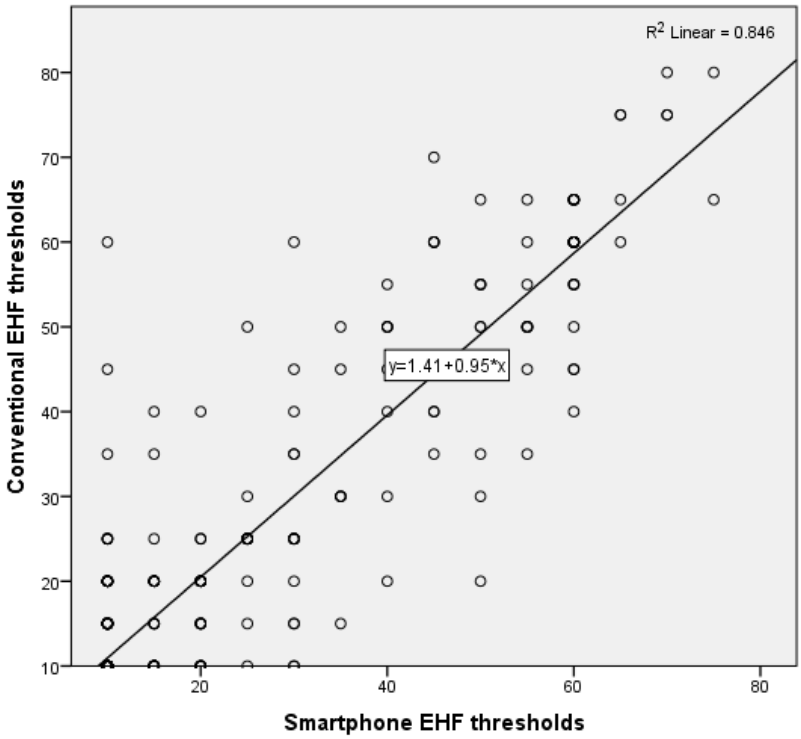

Figure 2. The relationship of thresholds (dB HL) determined with conventional EHF audiometry and smartphone EHF audiometry using non-standard audiometric headphones.

In 59.4% of threshold-seeking instances across all test frequencies for audiometric headphones, the participants obtained a 10 dB HL threshold, with both conventional and smartphone audiometry (Table 4). This correspondence was 57.6% for non-standard audiometric headphones. Thresholds, obtained through smartphone and conventional EHF audiometry, differed by ≤ 5 dB in 77% and 78.4% of threshold-seeking instances using audiometric and non-standard 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 non-standard audiometric headphones (Table 5).

Table 4.

Distribution (%) of thresholds for conventional audiometry (CA) and smartphone audiometry (SA) with audiometric and non-standard 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 & SA > 10 dB	20.5	22.1	23	35.2	25.2
CA > 10 dB & SA = 10 dB	12.3	10.7	9	9.8	10.6
SA > 10 dB & CA = 10 dB	5.7	4.9	2.5	4.1	4.3
Non-standard audiometric headphones (n= 122)					
10 dB for CA and SA	57.4	64.8	61.5	46.7	57.6
CA & SA >10 dB	22.1	20.5	27.9	42.6	28.3
CA > 10 dB & SA = 10 dB	9	13.1	4.1	5.7	8
SA > 10 dB & CA = 10 dB	9.8	0.8	3.3	4.9	4.7

Table 5.

Threshold correspondence (%) for conventional audiometry (CA) and smartphone audiometry (SA) with audiometric and non-standard audiometric headphones.

	0-5 dB	10 dB	> 15 dB
Comparisons including floor effect			
CA & SA with audiometric headphones	77	3.6	4.4
CA & SA with non-standard 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 non-standard audiometric headphones	78.7	2.6	2.5
Comparisons excluding floor effect			
CA & SA with audiometric headphones	70.2	12.7	15.1
CA & SA with non-standard 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 non-standard audiometric headphones	78.7	14.7	6.6

The overall average threshold difference, including thresholds at 10 dB HL, using audiometric headphones (1.2 ± 7.9), was poorer than for non-standard audiometric headphones (0.6 ± 6.3; Table 6). 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 non-standard 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, showed no significant differences between thresholds for conventional and smartphone audiometry, using audiometric headphones across frequencies all ($p>0.05$). When using non-standard audiometric headphones for smartphone EHF audiometry, also excluding those thresholds at 10 dB HL, the only significant difference was at 10 kHz ($p<0.05$).

Table 6.

Average differences between conventional audiometry (CA) and smartphone audiometry (SA) with audiometric and non-standard audiometric headphones.

	8 kHz	10 kHz	12.5 kHz	16 kHz
Average difference (SD; n)				
CA & 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 & SA with non-standard 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 & SA with audiometric headphones	1 (11.1; 25)	1.5 (7.9; 27)	0.9 (8.6; 28)	0.1 (11; 43)
CA & SA with non-standard 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 & 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 & SA with non-standard 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 & 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 & SA with non-standard audiometric	2.8 (2.5; 27)	8.0 (7.5; 25)	6.2 (6.4; 34)	8.2 (7.5; 52)

The overall average test-retest difference was similar for both audiometric headphones (0.7 ± 5.9) and non-standard audiometric headphones (0.7 ± 6.3), and not significantly different to that of conventional audiometry (0.8 ± 4.2; Table 7). Excluding thresholds at 10 dB HL, audiometric headphones (-1.4 ± 9.4) and conventional EHF audiometry (-0.6 ± 6.0) were lower than non-standard audiometric headphones (0.2 ± 6.3). Average absolute test-retest reliability differences were similar for audiometric (5.4 ± 7.6) and non-standard audiometric (5.0 ± 4.2) headphones. Test-retest reliability for smartphone EHF audiometry, using audiometric and non-standard audiometric headphones, including and excluding thresholds at 10 dB HL, showed no statistically significant differences across all frequencies ($p>0.05$).

Table 7.

Average test-retest reliability differences for conventional audiometry (CA) and smartphone audiometry (SA) with audiometric and non-standard 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 non-standard 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 non-standard 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 non-standard 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 non-standard audiometric headphones	3.5 (4.3; 13)	7.0 (2.7; 5)	3.8 (3.5; 8)	5.6 (6.3; 16)

3.5 DISCUSSION

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

The majority of thresholds were within the clinically acceptable 10 dB test-retest difference for EHF reported in previous studies (Frank, 1990; Frank and Dreibach, 1991). Excluding those thresholds at 10 dB HL, 93.4% of smartphone test-retest EHF thresholds, using non-

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

Previous studies on EHF audiometry reported similar test-retest correspondence. Frank (1990), and Frank and Dreibach (1991) reported that close to 95% of test-retest EFH 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 to insert earphones. Schmuziger et al (2004) found test-retest correspondence to be similar between 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 to 100% of EHF test-retest thresholds correspondence within 10 dB, using Koss HV/1A+ headphones and 88 to 98% using ER-2 insert earphones. Although these previous studies' results could be due the cohorts and their hearing levels, results for the current study, using audiometric headphones, excluding the thresholds at 10 dB HL, are within the general range by in 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 non-standard audiometric headphones (6.2 ± 6.0), were within 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 Dreibach (1991) found a ± 1.1 dB average test-retest threshold difference, which was almost similar to that found by Valente et al (1992), reporting 1.5 dB average test-retest difference, using Koss HV/1A+ headphones and 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 current study, using both audiometric and non-standard audiometric headphones, and excluding thresholds at 10 dB HL, were similar to these studies, indicating good reproducibility.

The standard deviation 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 non-standard audiometric headphones. However, these results showed a higher variability than that of Frank (1990), and Frank and Dreibach (1991), which ranged from 3.6 to 6.1 and 3.0 to 4.4, respectively. Van Tonder et al (2017) reported similar variability (SD's), ranging from 3.9 to 4.7 for the average absolute differences between conventional and smartphone audiometry across conventional frequencies (0.5, 1, 2, 4 and 8 kHz). The current study's average absolute threshold difference showed variability almost similar, but still higher than that of Van Tonder et al (2017). Although comparing two different 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 to 3.6 in the conventional frequency range.

The only significant difference between EHF threshold comparisons, between techniques (conventional vs smartphone) in the current study, was at 10 kHz, using non-standard 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 non-standard audiometric headphones, used in the current 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 non-standard audiometric headphones showed notches at 4 and 10 kHz and a low, sloping frequency response at 0.25 kHz.

Since all testing was conducted in a sound booth, application of smartphone audiometry 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 (Louw et al, 2017; Sandstrom et al, 2016). 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 health care settings in underserved areas, is important to establish.

A further limitation of this study was that smartphone audiometry 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 conventional and smartphone audiometry. A direct threshold comparisons could therefore only be made on a subset of actual thresholds unaffected by ant floor effect.

3.6 Conclusion

The current study demonstrates that accurate and reliable EHF thresholds can be determined by using a smartphone audiometry 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 form 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.

4. Discussion and Conclusion

4.1 Discussion

The current study is the first to utilise a smartphone-based audiometry application (app) with calibrated headphones to determine thresholds in the extended high frequency (EHF) range. Study findings demonstrate EHF threshold accuracy and reliability comparable to that of conventional audiometry.

The majority of thresholds were within the clinically acceptable 10 dB test-retest difference for EHF, reported in previous studies (Frank, 1990; Frank & Dreibach, 1991). Excluding those thresholds at 10 dB HL, 93.4% of smartphone test-retest EHF thresholds, using non-standard audiometric headphones, corresponded within 10 dB, which was almost identical to that of the current study's conventional EHF audiometry (93.3%).

Previous studies on EHF audiometry have reported similar or higher test-retest correspondence. Frank (1990), and Frank and Dreibach (1991) reported ≥95% of test-retest EFH thresholds corresponded within 10 dB difference 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 Sennheiser HDA 200 circumaural headphones, and Etymotic Research ER-2 insert earphones, ranging from 94 to 99% and 95 to 100% of EHF thresholds corresponding within 10 dB, respectively. Valente et al. (1992) reported 83 to 100% of EHF test-retest thresholds, corresponding within 10 dB using Koss HV/1A+ headphones and 88 to 98%, using ER-2 insert earphones. Results for the current study, using standard audiometric

headphones, excluding the thresholds at 10 dB HL, were slightly poorer but in line with the correspondence reported by Valente et al. (1992), using Koss HV/1A+ headphones, with 86.7% of thresholds within 10 dB test-retest difference.

The overall average absolute threshold differences, excluding thresholds at 10 dB HL, between conventional and smartphone EHF audiometry using standard audiometric headphones (6.5 ± 7.2) and non-standard audiometric headphones (6.2 ± 6.0), were within 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 Dreibach (1991) found a ± 1.1 dB average test-retest threshold difference, which was almost similar to that found by Valente et al. (1992) reporting 1.5 dB average test-retest difference, using Koss HV/1A+ headphones and 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 current study, using both standard and non-standard audiometric headphones and excluding thresholds at 10 dB HL, were similar to these studies, indicating good reproducibility.

The standard deviation for the average test-retest threshold difference, excluding thresholds at 10 dB HL, was higher for smartphone EHF audiometry, using standard audiometric headphones than for conventional EHF audiometry and smartphone EHF audiometry, using non-standard audiometric headphones. However, these results showed a higher variability than that of Frank (1990) and Frank and Dreibach (1991), which ranged from 3.6 to 6.1 and 3.0 to 4.4, respectively. Van Tonder et al. (2017) reported similar variability (SD's), ranging from 3.9 to 4.7 for the average absolute differences between conventional and smartphone

audiometry in the conventional frequencies (0.5, 1, 2, 4 and 8 kHz). The current study's average absolute threshold difference showed variability almost similar, but still higher than that of Van Tonder et al. (2017). Although comparing two different stimuli, John, Kreisman, and Kreisman (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 to 3.6 in the conventional frequency range.

The only significant difference between EHF threshold comparisons, between techniques (conventional vs smartphone) in the current study, was at 10 kHz, using non-standard 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 non-standard audiometric headphones used in the current 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 non-standard audiometric headphones showed notches at 4 and 10 kHz and a low, sloping frequency response at 0.25 kHz. This indicates that each headphone should be calibrated separately (Van der Aerschot et al., 2016).

4.2 Clinical Implications

The current study demonstrates that the hearTest smartphone app for EHF may provide a valid alternative for assessing hearing thresholds using an inexpensive Android device and calibrated headphones. As such, the hearTest smartphone app allows for mobile threshold testing and monitoring, as well as data storage onto a cloud server, allowing hearing healthcare professionals to access the results from any location. Specific populations that may benefit from this type of technology include those individuals receiving ototoxic medications

for the treatment of various cancers, tuberculosis, or HIV/AIDS, and those individuals exposed to harmful levels of occupational noise.

Although tuberculosis cases are declining globally, they still remain prominent in certain regions such as Africa and Asia (Dheda et al., 2017). The management of tuberculosis is further threatened by the emergence of resistance to anti-tuberculosis drugs (Dheda et al., 2017). It is estimated that approximately 5% of patients with tuberculosis either have multi-drug-resistant (MDR) or extensive drug-resistant (XDR) tuberculosis, however, this estimation is higher in some regions (Dheda et al., 2017; WHO, 2015). MDR tuberculosis implies a resistance to at least one major drug and a switch to second-line drug regimen when first-line therapy is unsuccessful (Dheda et al., 2017; WHO, 2015). XDR tuberculosis is MDR tuberculosis with a resistance to even second-line injectable drug therapies (Dheda et al., 2017; WHO, 2015). These injectable drugs selectively destroy the basal hair cells, which are required for high-frequency hearing (Seddon et al., 2012).

The significant increase in MDR tuberculosis has further been linked to the HIV epidemic (Harris, Bardien, et al., 2012; Harris, Peer, et al., 2012; Wells et al., 2007). Harris, Peer, et al. (2012) were some of the first to demonstrate an association between HIV infections and ototoxicity in patients on MDR tuberculosis treatment. Furthermore, patients who are HIV-positive are at a greater risk of hearing loss, due to otitis media, opportunistic central nervous system infections, malignancies, and ototoxic drug treatment (Chandrasekhar et al., 2000; Grimaldi et al., 1993; Harris, Bardien, et al., 2012; Little, Gardner, Acker, & Land, 1995; Meynard et al., 1997; Michaels, Soucek, & Liang, 1994). Additionally, 21-49 % of patients who are HIV-positive will develop a high frequency sensori-neural hearing loss (Birchall, Wight, French, Cockbain, & Smith, 1992; Chandrasekhar et al., 2000; Harris, Bardien, et al.,

2012; Soucek & Michaels, 1996). Auditory monitoring should, therefore, form an integral part of the treatment of patients suffering from MDR tuberculosis and HIV. Apart from tuberculosis and HIV, the majority of cancer cases have also come from low- and middle-income countries, another population necessitating auditory monitoring (Farmer et al., 2010). However, in these countries with limited resources, hearing loss in these patients goes undetected (Fagan & Jacobs, 2009; Harris, Peer, et al., 2012). Even in developed countries, early identification and monitoring of ototoxic hearing loss are not being implemented as a standard, due to audiometric equipment limitations and patients often being too ill, or fatigued, or do not have access to clinics (Jacobs et al., 2012). Concomitant noise exposure should also not be overlooked, as noise can further exacerbate an ototoxic hearing loss (Durrant et al., 2009).

These individuals require baseline hearing testing and regular monitoring in order to minimise the possibility of developing a hearing loss (Harris, Bardien, et al., 2012; Harris, Peer, et al., 2012). However, the actual implementation of an ototoxic monitoring programme can be challenging (Konrad-Martin et al., 2017). Therefore, by implementing smartphone technology, like the hearTest smartphone app, at primary health-care clinics and on-site of various industrial and manufacturing settings, these individuals could receive more regular hearing evaluations and possibly reduce the debilitating effects of a hearing loss. Additionally, for those individuals receiving ototoxic treatment, and who are often too ill to undergo hearing testing at a clinic, the hearTest smartphone app can be taken to the homes or hospital beds of these individuals, in order for their hearing to be assessed (Sandstrom et al., 2016; Van Tonder et al., 2017).

With the possibility of increased access to EHF monitoring, the next consideration is EHF audiometry guidelines. Well-developed guidelines exist for hearing screening and testing, in general, for adults and children of various ages (ASHA, 2005; British Society of Audiology, 2004;), though current international guidelines, specific to ototoxic monitoring, are limited (Seddon et al., 2012). The American Academy of Audiology issued a position statement and clinical practice guideline regarding ototoxic monitoring (Durrant et al., 2009), where the authors discussed the use of conventional audiometry, OAE's and EHF in the test battery, the different challenges of each, as well as hearing loss classification, suggesting that the ASHA classification should be used. However, these guidelines include extensive test protocols performed by an audiologist in an audiometric booth. This approach may be too comprehensive and taxing for patients suffering from life-threatening illnesses and cost prohibitive if it requires serial clinical appointments (Brungart et al., 2017). Also, these guidelines do not, however, advise on the testing and monitoring of patients in low-resource settings, where the majority of drug resistant tuberculosis patients live (Seddon et al., 2012). The WHO Guidelines for the programmatic management of drug-resistant tuberculosis (2011), on the other hand, states that hearing should be documented and compared with baseline results, if audiometry is available. When a hearing loss is detected, management options include either changing or discontinuing the drug regimen. However, the guidelines do not specify how the hearing should be tested, how often it should be tested, and what classifies as a hearing loss. By implementing the more accessible smartphone EHF audiometry, such as the hearTest app, ototoxicity monitoring guidelines specific to resource-limited regions may be developed, and allow for the further standardisation of the processes involved in the testing and monitoring of these individuals receiving ototoxic medication.

Another possible area of research, where smartphone EHF audiometry can prove useful, is in the recent emergence of cochlear synaptopathy, referred to as a "hidden" hearing loss, in that the conventional test battery yields normal results. Recent animal studies of noise-induced and age-related hearing loss has suggested that cochlear synaptopathy could possibly contribute to difficulties in understanding speech in noise, tinnitus, and hyperacusis, even when the conventional audiogram shows normal thresholds (Hickox & Liberman, 2014; Kobel et al., 2016; Kujawa & Liberman, 2015; Liberman & Kujawa, 2017; Liberman & Liberman, 2015). These authors believe that cochlear synaptopathy may be widespread in acquired sensorineural hearing loss. Yet, no evidence relating to the human population has been demonstrated, as the necessary anatomical evidence to confirm cochlear synaptopathy presents with some limitations. In the study done by Liberman et al. (2016), the authors divided the participants into a low-risk and high-risk group based on self-reported noise exposure. They assessed cochlear function using otoacoustic emissions and click-evoked electrocochleography, while hearing was assessed using behavioural audiometry and word recognition with or without noise, or time compression and reverberation. Electrocochleography results demonstrated differences in ratio of the summating potential (SP) and action potential (AP), suggesting hair cell dysfunction. Those participants in the high-risk group showed elevated EHF thresholds, further suggesting cochlear dysfunction, which was again supported by the differences in high frequency DPOAE's. The high-risk group also showed significantly poorer word recognition scores in noise or with time compression and reverberation. These authors therefore suggested that a combination of ear-canal electrocochleography, EHF audiometry and word-recognition tests might be useful in identifying the early signs of noise damage to hair cells and neurons typical of synaptopathy, which would otherwise be missed with standard audiometry. Hickox and Liberman (2017) also suggests that, should EHF audiometry and OAE's be included in the monitoring of

NIHL and ototoxic drugs, it could be valuable in detecting early signs of synapse and hair cell loss. Smartphone EHF audiometry, together with OAE's, can, therefore, be considered as non-invasive assessment tools to possibly diagnose cochlear synaptopathy in individuals, not only in developed countries, but in developing countries, where the incidence of ototoxicity due to tuberculosis and cancer treatment are high (Dheda et al., 2017).

4.3 Critical Evaluation

A critical evaluation of the research project is important, in order to interpret the findings of the research within the framework of its strengths and limitations. These are highlighted below.

4.3.1 Study Strengths

The current study was the first to investigate the accuracy and reliability of the extended high frequencies, using smartphone technology. The specific study used an inexpensive, entry-level Android smartphone and calibrated standard audiometric Sennheiser HDA 300 circumaural headphones, as well as commercially available Sennheiser HD 202 II supra-aural headphones. Equivalent thresholds sound pressure levels (ETSPL's) have recently been measured for the commercially available headphones (Van der Aerschot et al., 2016).

A second strength was the implementation of a repeated measures design to direct the current study. Besides controlling for factors that could cause variability between subjects, the repeated measured design allowed the test-retest reliability to be determined. Although a possible disadvantage of such a design is the order effects, counterbalancing was used in an attempt to reduce the likelihood of the test order affecting threshold comparisons.

The selection criterion specified that a range of hearing sensitivity should be included in the study. A third strength therefore, was that almost half of the participants sampled were receiving possible ototoxic treatment (41.6%), that allowed for a representative sample of those with normal hearing, and a possible hearing loss. Apart from these participants possibly presenting an ototoxic hearing loss, they form part of one of the populations that may benefit from this type of smartphone technology, in detecting a hearing loss early on.

4.3.2 Study Limitations

Although almost half of the participants sampled had a history of receiving possible ototoxic medications, only eight participants (13.1%) presented with a sensorineural hearing loss. A larger sample size of participants with sensorinerual hearing loss would ensure a more representative distribution of people to whom the results could be generalised.

A second limitation was the influence of a possible floor effect. As the hearTest app only tested down to 10 dB HL, this resulted in a number of thresholds being unspecified. In 59.4% of instances across all test frequencies for audiometric headphones, the participants recorded at 10 dB HL threshold with both conventional and smartphone audiometry. This correspondence was 57.6% for non-audiometric headphones. This implies that, for only 4.3% and 4.7% of cases, could a real comparison be made between the thresholds of the two modes of testing. This limits the evidence to translate these methods into a screening tool, in that there were not enough samples to properly compare pairs of thresholds that were above 10 dB.

Although it is important to determine the validity of the hearTest in a controlled environment, it is yet to be determined in a clinical environment outside of a sound booth. Therefore, a possible third limitation is that testing was conducted outside of a sound booth, and its mobility and usefulness within these mobile contexts, e,g community and primary healthcare clinics, could not be determined.

4.4 Recommendations for Future Research

The critical evaluation of the present study, and consideration of the significance of the results obtained, suggest several future research implications with the hearTest app.

- The validity of EHF smartphone testing outside of a sound booth can be investigated, which may allow for a more readily available and mobile solution in detecting a high frequency hearing loss early on, in both developing and developed countries, in a real life environment. This could allow for significant cost reductions in purchasing hearing healthcare equipment, and can especially be implemented at community- and primary health-care clinics, TB clinics, and occupational contexts, where resources are limited.

- Since the current study had too few sample pairs to compare thresholds that were above 10 dB HL, the effectiveness of the hearTest to determine accurate thresholds above 10 dB HL can, therefore, be determined in order to determine its ability to detect a hearing loss.

- A further recommendation may be to determine the accuracy in detecting threshold shifts between baseline and monitoring audiograms in specific populations, e.g. patients receiving ototoxic medications or hearing conservation programs and, therefore, to be able to detect a significant change in hearing as early as possible.

- A recent study investigated the test-retest reproducibility of narrow-band noise (NBN) versus pure tone stimuli of conventional and EHF thresholds (John et al., 2017). The authors found comparable test-retest reproducibility for NBN, however, they cautioned against direct comparison to pure tone stimuli, as it could lead to an underestimation of hearing loss. However, NBN is particularly used for assessing infants and young children, in order to obtain and maintain their attention. Patients receiving ototoxic medications, who are too ill to visit a primary health-care clinic for a hearing evaluation, and need to be tested at their home or at their hospital beds, may even be too tired to concentrate during testing. The use of NBN rather than pure tone stimuli may maintain their attention during testing better. Future research could, therefore, investigate the reliability of NBN testing for smartphone EHF audiometry.

4.5 Conclusion

Smartphone audiometry can increase access to hearing health care in underserved and remote areas (Clark & Swanepoel, 2014; Mahomed-Asmail et al., 2016; Sandstrom et al., 2016; Swanepoel et al., 2010; Swanepoel, Myburgh, Mahomed, & Eikelboom, 2014). The current study demonstrates that accurate and reliable EHF thresholds can be determined, using a smartphone audiometry application on an Android platform, coupled with calibrated headphones. This may provide a mobile, affordable option for EHF audiometry in communities. Persons receiving ototoxic medications or, who are exposed to loud noise levels, with limited access to these hearing healthcare services, in particular, may be targeted with this type of technology. It also holds promise for further research possibilities and advances in specific areas, such as developing standard guidelines for testing in resource-limited areas.

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APPENDICES

APPENDIX A

Ethical Clearance Form: Faculty of Humanities

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Research Ethics Committee

27 March 2015

Dear Prof Vinck

Project:	**Validation of hearTest smartphone application for extended high frequency hearing thresholds**
Researcher:	**ME Bornman**
Supervisor:	**Prof DCD Swanepoel**
Department:	**Speech-Language Pathology and Audiology**
Reference number:	**10153064 (GW20150324HS)**

Thank you for the **well written** application that was submitted for ethical consideration.

I am pleased to inform you that the above application was **approved** by the **Research Ethics Committee** on 26 March 2015. Data collection may therefore commence.

Please note that this approval is based on the assumption that the research will be carried out along the lines laid out in the proposal. Should the actual research depart significantly from the proposed research, it will be necessary to apply for a new research approval and ethical clearance.

The Committee requests you to convey this approval to the researcher.

We wish you success with the project.

Sincerely

Prof Karen Harris
Acting Chair: Research Ethics Committee
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail:Karen.harris@up.ac.za

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Research Ethics Committee

27 March 2015

Dear Prof Vinck

Project:	**Validation of hearTest smartphone application for extended high frequency hearing thresholds**
Researcher:	**ME Bornman**
Supervisor:	**Prof DCD Swanepoel**
Department:	**Speech-Language Pathology and Audiology**
Reference number:	**10153064 (GW20150324HS)**

Further to our letter of approval, please note that this approval will be rescinded should the Dr George Mukhari Hospital not give permission for the student to conduct the research. Written proof of this permission is therefore required.

Sincerely

Prof. Karen Harris
Acting Chair: Research Ethics Committee
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail: Karen.harris@up.ac.za

APPENDIX B

Letter of Permission: Dr George Mukhari Academic Hospital

GAUTENG PROVINCE
HEALTH
REPUBLIC OF SOUTH AFRICA

Dr. George Mukhari Academic Hospital

Office of the Director Clinical Services
Enquiries : Dr. PMT. Mabusela
Tel : (012) 529 3880
Fax : (012) 560 0099
Philly.mabusela@gauteng.gov.za
kedibone.matsimela@gauteng.gov.za

To : Ms. ME Bornman
: Department of Speech-Language Pathology & Audiology
: University of Pretoria
: Private Bag X 20
: Hatfield, Pretoria
: 0028

Date: 04 May 2015

RE : PERMISSION TO CONDUCT RESEARCH.

The Dr. George Mukhari Academic Hospital hereby grants you permission to conduct research on "Validation of hearTest Smartphone application for extended high frequency hearing thresholds at Dr. George Mukhari Academic Hospital."

The hospital is aware that you have already obtained Clearance from the University of Pretoria

We note that you have already obtained ethical Clearance from the Human Research Ethics Committee.

☐ This permission is granted subject to the following conditions:
That the Hospital incurs no cost in the course of your research.

☐ That access to the staff and patients at the Dr George Mukhari Academic Hospital will not interrupt the daily provision of services.

☐ That prior to conducting the research you will liaise with the supervisors of the relevant sections to introduce yourself (with this letter) and to make arrangements with them in a manner that is convenient to the sections.

Yours sincerely

DR. PMT. MABUSELA
DIRECTOR: CLINICAL SERVICES

APPENDIX C

Letter of Informed Consent: Dr George Mukhari Academic Hospital Participants

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology & Audiology

INFORMED CONSENT FORM

RE: Research project on clinical validity of smartphone-based high frequency audiometry

I (Martèlle Bornman) would like to invite you to participate in this research study that I am undertaking as requirement for my Masters degree in Communication Pathology (Audiology).

This Informed Consent Letter is for men and women who are patients of the Speech therapy & Audiology Department at Dr George Mukhari Academic Hospital (DGMAH). You are receiving this informed consent form to request your participation in a research project, which will investigate the accuracy and reliability of the smartphone application hearTest ® for detecting hearing thresholds.

The Informed Consent Form has two parts

- Information Sheet (to share information about the research with you)
- Certificate of Consent (for signatures if you agree to take part)

It would be appreciated it if you could take the time and effort to read through the Informed Consent Form. If there are any uncertainties regarding this research you are welcome to contact me (contact details on page 4).

Kind regards,

Martèlle Bornman
Student researcher

Prof. De Wet Swanepoel
Supervisor

PART 1: INFORMATION SHEET

Introduction

The purpose of this information sheet is to explain why this research is being done; why you have been asked to participate; and what you will be asked to do for the research.

The choice to participate in the research is entirely yours. Please read through this information sheet in order to make your decision. There may be words or concepts that you may not understand. Please feel free to ask regarding any uncertainties.

What is the Purpose of the Research?

Recent studies have showed that is possible to use smartphone applications to test the hearing of different people (Chi Shan Kam *et al*., 2012; Clark & Swanepoel, 2014; Khoza-Shangase & Kassner, 2013; Szudek *et al*., 2012; Swanepoel, Myburgh, Mahomed, & Eikelboom, 2014). The study done by Swanepoel, Myburgh, Mahomed, and Eikelboom (2014) showed that the smartphone application (hearScreen™) can be accurately calibrated for audiometry. Also, the results were similar to conventional school-based hearing screening.

Using a smartphone-based solution, that is portable and integrates data capturing and uploading capabilities, will reduce cost. A recent development from the hearScreen™ application is the hearTest version that allows for threshold determination at conventional and extended high frequency ranges. Its clinical accuracy and reliability has not been determined however.

Therefore this study's purpose is to determine the validity of the hearTest smartphone application for high frequency hearing testing and it's possible use in monitoring patients' hearing who are at-risk for ototoxicity.

Why have I been chosen?

All adult patients from the Speech therapy & Audiology Department at Dr George Mukhari Academic Hospital are invited, and who are:

- Between the ages of 18-65.
- Who have normal hearing,
- or developed a hearing loss at any stage of their lives.

Do I have to take part?

Your participation in this research is completely voluntary. You can choose whether you want to participate or not. Whether you choose to participate or not, all the services you receive at the Speech therapy & Audiology Department at DGMAH will continue as usual. If you choose not to participate in this research project, it will not be held against you in any way.

What will I do if I take part?

If you participate in the research, you will be asked to do a series of hearing tests. These tests all determine the softest sound that you can hear for different frequencies (pitches). During the testing, you will be required to sit in

a soundproof booth and listen to several sounds played through different headphones. You will need to respond to these sounds by pressing a respond button or the virtual respond button on the smartphone screen (more detail about each of the tests can be found in the table below). These tests are easy to perform.

TESTS	WHAT WILL YOU HEAR	WHAT WILL YOU DO
Gold standard high frequency audiometry with audiometric headphones.	High frequency sounds decreasing and increasing in intensity (loudness).	Press the respond button whenever you hear the sound.
The hearTest smartphone application with audiometric headphones.	High frequency sounds decreasing and increasing in intensity (loudness).	Press the virtual respond button on the smartphone screen whenever you hear the sound.
The hearTest smartphone application with audiometric headphones.	High frequency sounds decreasing and increasing in intensity (loudness).	Press the virtual respond button on the smartphone screen whenever you hear the sound.

Lastly, you will be asked to repeat only one of the three above-mentioned tests.

How long will the test take?
The tests will take about an additional 15 minutes to your diagnostic hearing test to complete and you will only be tested on one occasion.

Where will I need to go?
The tests will take place in a sound proof booth at Dr George Mukhari Academic Hospital in the Speech therapy & Audiology Department.

What are the possible risks?
This study does not involve any invasive procedures. There are no risks involved if you decide to participate in this study, and you will not be harmed in any way.

What are the possible benefits?
There are no direct benefits of participating, and no reimbursement will be given for your participation. However, the information obtained from this study may help us in determining the validity of the smartphone application as well as to conduct further research to improve the monitoring of high frequency hearing thresholds for patients at-risk of ototoxicity.

What about confidentiality?
All information collected during the research will be kept confidential and only be seen by the researcher. Your name will not be mentioned in the research and any information used concerning you will be given a number instead of your name. Only the researcher will know what your number is and this information will not be given to anyone else.

The results of the research will be stored at the Department of Speech-Language Pathology and Audiology for a period of 15 years as is policy by the University of Pretoria. This data will be locked away and unavailable to anyone else besides the researcher. The results of this study will be stored in the form of Excel sheets and saved on a compact disk (CD). All data use adheres to the terms of the Data Protection Act (DPA, 1998).

How will the results be shared?
The knowledge obtained from the research will be reported in the form of an article and submitted for publication in a recognised, accredited international journal. This article will be available to professionals in the field of Audiology and eHealth. If you would like a summary of the findings after the research has been completed, you can indicate so in the Certificate of Consent form.

Can I refuse or withdraw from the research?
You do not have to partake in this research if you do not wish to do so. You may also stop participating in the research at any time you choose. If you choose to stop participating in the research all your rights will be maintained. Should your data already be collected at that stage, your data will be excluded from the study.

What if there is a problem?
If you have any questions or concerns about any aspect of the research project please feel free to contact me at any time.

Researcher	*Supervisor*
Martèlle Bornman: *Tel:* 0824381229 *Email:* mart.bornman@gmail.com	Prof De Wet Swanepoel *Tel:* 012-4204280 *Email*: dewet.swanepoel@up.ac.za

Thank you for taking the time to read this Information Sheet

Please indicate whether you want to participate or not in the *Certificate of Consent* form attached

PART 2: CERTIFICATE OF CONSENT

Please mark the appropriate questions with an x.

1. I agree to take part in the above mentioned research project.

YES ☐

NO ☐

ONLY TICK QUESTIONS 2-9 IF YOU ANSWERED YES IN QUESTION 1

2. I confirm that I have read and understood the form entitled *Information Sheet* for the above research project. Any questions or concerns about the study have been addressed and dealt with adequately. ☐

3. I understand that my participation in the research is entirely voluntary. I acknowledge the fact that I am allowed to withdraw from the research at any time and that this decision will not be held against me in any way. ☐

4. I understand that I will have to perform four different tests and that I will only be tested once if I choose to participate in this study. ☐

5. I understand that the researcher will not identify me by name in any reports, and that all information about me will be kept confidential. ☐

6. I understand that there are no financial benefits involved with participating in the study. ☐

7. I understand all my rights as a research participant. ☐

8. I know whom to contact about any concerns regarding the research project. ☐

9. I would like to receive a summary of the results of the research project, once completed.

   YES ☐

   NO ☐

_____	_____	_____
Name of participant	Signature	Date

Martèlle Bornman:
Tel: 0824381229

APPENDIX D

Letter of Informed Consent: University of Pretoria Prospective Students Participants

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Faculty of Humanities
Department of Speech-Language Pathology & Audiology

Dear Junior Tukkie student

We are currently conducting a project with the aim of determining the validity of the hearTest smartphone application for extended high frequencies. The goal of this project therefore is to determine the accuracy and test-retest reliability of the smartphone application when compared to gold standard audiometry. Participants will be tested with the smartphone application and gold standard extended high frequency audiometry. Testing should take 30 minutes to complete. Participation in this project is voluntary and you may withdraw from the study at any time should you wish to do so.

The data gathered through this study will be stored in a manner that will ensure confidentiality and anonymity. In line with the policies of the University, the data will be stored in electronic format for a period of 15 years for research and archiving purposes. Results of the study will be reported in a scientific article, and may also be used for further research and/or teaching purposes.

If you are willing to participate in this study, please sign the informed consent form below.

Many thanks for your participation in this important research.

Martelle Bornman
Masters Student Researcher

Prof De Wet Swanepoel, PhD
Professor of Audiology

Informed consent form

I, _____ hereby give voluntary consent to participation in the research project as explained to me in the attached instructions. The nature and goal of the project has been explained to me. I understand that I have the right to choose if I want to participate in the project and that the data gathered through this project will be handled with confidentiality. I am aware that the results might be published.

Signed: _____ Date: _____

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APPENDIX E

Recording sheet

ID number/DoB:		**Participant nr:**
Age:	**Gender:**	**Ethnic group:**

Audiometric testing		
	Right	Left
Otoscopy		
Tympanometry		
Audiogram		

Comments:

_____

_____

_____

_____

Extended high frequency testing								
Test frequency	**Test 1** GS / AH / NH		**Test 2** GS / AH / NH		**Test 3** GS / AH / NH		**(Re)test 4** GS / AH / NH	
	Right	Left	Right	Left	Right	Left	Right	Left
8 000 Hz								
10 000 Hz								
12 500 Hz								
16 000 Hz								

Notes: _____

_____

_____

_____