Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence

By

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A dissertation submitted in fulfilment of the requirements for the degree

MA AUDIOLOGY

In the Department of Speech-Language Pathology and Audiology
FACULTY OF HUMANITIES
UNIVERSITY OF PRETORIA

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November 2020

ACKNOWLEDGEMENTS

I would like to extend my sincere gratitude as follows:

- To my Heavenly Father who gave me the strength and opportunity to complete my studies;
- To my supervisors, Prof Leigh Biagio de Jager and Prof Bart Vinck for your guidance and support;
- To Dr Louis Hofmeyr for his input and sharing his expertise knowledge;
- To the otolaryngologist and audiologists who assisted me in sourcing SSCD participants;
- To all the participants for their time and willingness to participate in my study;
- To my friends, family and colleagues who supported me throughout my studies;
- To my niece Suné for ongoing support, advice and Excel help;
- To my mother for her love and support and believing in me;
- I would like to dedicate this dissertation to my late father, who always encouraged me to study, and who would have been so proud.

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LIST OF ABBREVIATIONS

AM:	**Admittance Magnitude**
CT:	**Computed Tomography**
cVEMP:	**Cervical Vestibular Evoked Myogenic Potential**
eCochG:	**Electrocochleography**
ER:	**Energy Reflectance**
MEP:	**Middle Ear Pressure**
OCD:	**Ossicular Chain Discontinuity**
oVEMP:	**Ocular Vestibular Evoked Myogenic Potential**
PR:	**Power Reflectance**
R:	**Reflectance**
RF:	**Resonance Frequency**
SCC:	**Semicircular Canal**
sSCC:	**Superior Semicircular Canal**
SD:	**Standard Deviation**
SSCD:	**Superior Semicircular Canal Dehiscence**
TM:	**Tympanic Membrane**
TPP:	**Tympanometric Peak Pressure**
VEMP:	**Vestibular Evoked Myogenic Potential**
WAI:	**Wideband Acoustic Immittance**
WBT:	**Wideband Tympanometry**

ABSTRACT

Objective: The apparent effect of superior semicircular canal dehiscence (SSCD) on middle ear- and cochlear impedance has led researchers to investigate the use of wideband acoustic immittance as a screening tool when SSCD is suspected. The purpose of the study was to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at tympanometric peak pressure (TPP) and at ambient pressure.

Methods: Wideband Acoustic Immittance was performed at ambient pressure and at TPP on ten participants (12 ears) with confirmed SSCD, as well as on an age- and gender matched control group (12 ears). Inferential statistics were used to determine whether statistical differences existed for the absorbance values at each of the averaged frequencies, the resonance frequency (RF) and tympanometric data between the SSCD and control groups.

Results: The mean absorbance of the SSCD group reached a maximum at 890.9 Hz and a minimum at 6349.6 Hz. When testing absorbance at TPP, a statistically significant increase/peak in the absorbance values of the SSCD group (compared to those of the control group) was found from 630 to 890.9 Hz and a decrease from 4489.8 to 6349.6 Hz. Similar patterns were observed for absorbance at ambient pressure. A lower mean RF for ears with SSCD as well as an increased mean admittance magnitude (AM) value at RF was found compared to those of the control group.

Conclusions: The peak in absorbance around 890 Hz that was found on SSCD ears in the current study is similar to findings from earlier studies that found a peak in absorbance/notch in reflectance around 1000 Hz, reiterating its use as a screening tool when SSCD is suspected. No significant difference was found between absorbance measured at ambient pressure and at TPP in the current study; however, the stringent inclusion criteria with regard to TPP most likely affected this outcome. As a result of the significant difference in RF of SSCD ears compared to the RF of the control group, the potential value of measuring the RF of the middle ear as well as AM at the RF, to differentiate between mass-and stiffness dominated pathologies, was also illustrated. Further research measuring the AM at RF in normal

and pathological ears was suggested for comparison to the current study and to determine its clinical value.

Keywords: Superior semicircular canal dehiscence, wideband acoustic immittance, wideband tympanometry, wideband absorbance, resonance frequency, admittance magnitude.

1. CHAPTER ONE: INTRODUCTION

Since the development of the first device to record acoustic impedance at various ear canal pressures by Terkildsen and colleagues in 1959, tympanometry has become one of the most frequently performed components of the basic audiologic evaluation (Hunter & Sanford, 2014). Following Terkildsen's lead, most clinical instruments continued to measure acoustic immittance mainly at a single low probe frequency of 226Hz (Margolis, Saly, & Keefe, 1999), or 1000 Hz for infants. However, it was soon realised that the use of single frequencies could not provide sufficient information on the complete status of the middle ear, and that they were limited in differentiating various middle ear conditions, especially at frequencies above 2000 Hz (Margolis et al., 1999).

Investigators subsequently started exploring the use of broadband measures of middle ear function, which provided a more comprehensive view of the middle ear's acoustic response over a wide range of frequencies. Wideband acoustic immittance (WAI) tests provide this broadband view of middle ear function (Hunter & Sanford, 2014). WAI refers to a family of middle ear acoustical measures obtained across a wide frequency range including pressure reflectance, admittance, and the acoustic stapedius-muscle reflex (Feeney et al., 2017). WAI measurement theory takes advantage of the fact that when sound is presented to the external ear canal, some of the sound is absorbed by the middle ear and transferred into the inner ear, whereas some of the sound is reflected back along the ear canal (Hunter & Sanford, 2014). The ratio between the reflected pressure wave and the incident wave is described quantitatively as the reflectance (R). Similarly, the fraction of energy that is reflected can be described quantitatively by the energy reflectance (ER), also known as power reflectance (PR), such that ER = 1 indicates all energy is reflected and ER = 0 indicates that no energy is reflected (Voss, Horton, Woodbury, & Sheffield, 2008). Its complement (1 - ER) is known as energy absorbance (Sun, 2016).

The diagnostic significance of WAI testing in patients with middle ear dysfunction has been the subject of various research studies to date (Merchant, Merchant, Rosowski, & Nakajima, 2016; Nakajima et al., 2012; Sanford & Brockett, 2014; Voss, Merchant, & Horton, 2012) and is still being explored extensively. Absorbance patterns for pathologies such as otosclerosis, otitis media with effusion and ossicular chain

discontinuity have already emerged and new potential benefits are being investigated (Ellison et al., 2012; Nakajima, Rosowski, Shahnaz, & Voss, 2013). One such WAI pattern of absorbance is that of individuals with Superior Semicircular Canal Dehiscence (SSCD).

SSCD was first described by Minor, Solomon, Zinreich and Zee (1998). The presence of vertical nystagmus after sound (Tullio phenomenon) or pressure (Hennebert sign) led the researchers to suspect a defect at the level of the superior semicircular canal (sSCC). Subsequent computed tomography (CT) revealed a dehiscence of the bone overlying the sSCC, acting as a "third window" (in addition to the round and oval windows) (Minor et al., 1998). In addition to sound- and pressure-induced vertigo and chronic disequilibrium, patients with SSCD can also present with auditory symptoms such as a low frequency conductive hearing loss, conductive hyperacusis, autophony, aural fullness and pulsatile tinnitus (Merchant et al., 2015).

The use of temporal bone CT images with a slice thickness of less than 1 mm (ideally 0.625 mm or less), with orientation in the plane of the sSCC (Pöschl view) and orthogonal to it (Stenvers view), has been recommended to improve diagnostic accuracy (Ward, Carey, & Minor, 2017). However, Ward et al. (2017) warn that CT imaging alone is not sufficient for diagnosis of SSCD and may mislead the ordering physician. Tavassolie, Penninger, Zuniga, Minor and Carey (2012) further cautioned that CT scans should not be taken as the sole evidence of SSCD, but that the findings should be considered in the context of the patient's symptoms and results of other tests such as the audiogram, vestibular evoked myogenic potential (VEMP) testing, acoustic reflexes, electrocochleography (eCochG) and observation of nystagmus in response to pressure or sound changes.

Regardless of the diagnostic criteria being followed, SSCD is still considered by many as the great otologic mimicker of other diseases, such as otosclerosis and perilymph fistula (Merchant et al., 2015). In many cases, incorrect diagnosis leads to unnecessary exploratory surgery or unresolved symptoms. Merchant et al. (2015) further suggested that an inexpensive and quick test that would support the need for a CT-scan would be of great value.

The middle ear serves to partially overcome the impedance mismatch between sound waves in air and the fluid-filled cochlea (Feeney & Sanford, 2004). Under

normal conditions, sound pressure conduction by the stapes results in only cochlear hair cell deflection due to the round window which dissipates cochlear vibration by impedance matching (Wick, Megerian, Manzoor, & Samaan, 2017). A dehiscence in the bone overlying the sSCC causes the energy that is typically confined to the cochlea to escape toward the dehiscence, resulting in displaced endolymphatic fluid within the SSC (Wick et al., 2017). With a SSCD, a change in the pressure within the vestibule acts as a driving force for the flow of fluid from the vestibule to the dehiscence, and with air-conducted sound such a dehiscence may act as a shunt path that decreases the cochlear input impedance (Rosowski, Songer, Nakajima, Brinsko, & Merchant, 2004). Rosowski et al. (2004) also noted a similarity in the results of laser-Doppler vibrometer velocity magnitude and angle between ears with SSCD and ossicular interruption, suggestive of an SSCD-induced decrease in the load on the tympanic membrane (TM) as might be caused by a decrease in cochlear impedance.

The apparent effect of SSCD on middle ear- and cochlear impedance has led researchers to investigate the use of WAI in the assessment of SSCD (Demir et al., 2019; Merchant et al., 2016, 2015; Nakajima et al., 2012). In a study by Nakajima et al. (2012) to determine the effect of a conductive loss on ear canal reflectance, PR was measured on 11 adult ears with confirmed SSCD. The results demonstrated a notch/decrease in PR (or a peak/increase in absorbance level) around 1000 Hz. Combined with audiometry results, the PR measurements exhibited 100% sensitivity and 95% specificity in differentiating between SSCD, stapes fixation, and ossicular discontinuity (Nakajima et al., 2012).

In a more recent study, Merchant et al. (2015) investigated whether PR measurements coupled with a detection algorithm sensitive to specific SSCD features, could act as a SSCD screening test for patients with varying symptoms (vestibular and/or hearing related), in order to ensure accurate recommendations for further assessment and management. Results showed that ears with SSCD (confirmed by high resolution CT-scan) generally exhibited a notch near 1000 Hz in the PR curves, thereby supporting the findings of Nakajima et al. (2012). Through the use of a notch-detecting algorithm, Merchant et al. (2015) was further able to separate SSCD from non SSCD ears with sensitivities of 80% to 92% and specificities of 69% to 72%. Merchant et al., (2015) concluded that the PR notch

near 1000 Hz seen in ears with SSCD is likely related to the effect of inner-ear dehiscence on cochlear impedance and ossicular motion, and that such notches could result from a decrease in cochlear damping. Although cochlear damping would exaggerate any TM-ossicular resonances, causing a notch in the PR, Merchant et al. (2015) state that a shift in the middle ear resonance frequency (RF) may also be responsible for the occurrence of a notch.

In a subsequent study by Merchant et al. (2016), human cadaveric temporal bones were manipulated to simulate SSCD, stapes- and malleus fixation, and ossicular disarticulation. An advantage of their method was that the effect of the simulated pathology could be measured before and after the manipulation, ensuring a controlled assessment of the effect of the pathology on their measurements, as opposed to only comparing the results to normative WAI data, where substantial variability still exists in the normal range. In this study, PR tests revealed that disarticulation resulted in relatively sharp decreases (notches) near 500 Hz (represented as an increase in absorbance), while SSCD tended to produce smaller notches in PR that occurred at a higher frequency (near 1000 Hz). These results were consistent with those found in adult patient populations (Merchant et al., 2015; Nakajima et al., 2012). Merchant et al. (2016) again attributed the presence of notches to the increasing effect of mechanical resonances in the ear, perhaps due to a decrease in damping at the TM, as SSCD decreases the resistive load of the inner ear on the TM.

In the aforementioned studies that explored the effect of SSCD on WAI, measurements were predominantly performed at ambient pressure. A recent study by Demir et al. (2019) investigated whether wideband tympanometry (WBT) can be used as a screening test for SSCD. Although pressurized measurements were performed, results in this study were reported on absorbance values measured at ambient pressure (Demir et al., 2019). Several research studies have suggested that measuring absorbance at tympanometric peak pressure (TPP) would allow for a determination of the functional status of the middle ear that would not be compromised by middle ear pressure (MEP) effects (Feeney, Grant, & Marryott, 2003; Margolis, Paul, Saly, & Schachem, 2001; Margolis et al., 1999; Shaver & Sun, 2013). Negative or positive MEP may mask the presence of concomitant middle ear diseases. Therefore, to improve specificity in assessing clinical/subclinical conditions

of the middle ear in patients with concurrent negative middle ear pressure, the latter should be temporarily counterbalanced with an equivalent ear canal pressure (Shaver & Sun, 2013).

Measuring WAI at TPP is of particular importance in SSCD, taking into account that the effect of SSCD on reflectance/absorbance occurs predominantly in the region of 1000 Hz (Merchant et al., 2016, 2015; Nakajima et al., 2012). In a study on humans and chinchillas, Margolis et al. (2001), referring to a study on normal hearing adults (Margolis et al., 1999) mentioned that pressurizing the ear canal increases reflectance for frequencies below 4000 Hz, and causes a decrease in reflectance in the 4000-8000 Hz region. The largest differences occurred in the 1000-2000 Hz region where pressurizing the ear produced large increases in reflectance. Margolis et al. (2001) concluded that reflectance results at any single ear-canal pressure (including ambient pressure) do not completely characterize the effects of middle ear pathology. Robinson, Thompson and Allen (2016) studied the effect of negative MEP on WAI and also found that the power absorbance level is most sensitive to negative MEP from 800 to 1900 Hz. Measuring WAI at TPP would, therefore, aid in further establishing a descriptive absorbance pattern for SSCD ears with the added benefit of eliminating the potential effect of middle ear pressure on the absorbance pattern.

Another advantage of measuring WAI at TPP is the ability to extract the RF of the middle ear from the results. Merchant et al. (2015) suggested that a shift in the middle ear RF, due to a change in the total stiffness of the middle and inner ear, may contribute to the occurrence of a PR notch in SSCD ears. The RF can be defined as the lowest frequency at which the spring (or stiffness) and mass elements of the outer and middle ear structures contribute equally to admittance (Shanks, 1984). Using multifrequency tympanometry, several authors reported the mean resonance of the human middle ear to lie between 800 Hz and 1200 Hz (Shanks, 1984), 990 Hz and 1315 Hz (Margolis & Goycoolea, 1993) and 789 Hz and 1043 Hz (Shahnaz & Polka, 1997), depending on the compensation method used. This method had its limitations though, since a restricted range of probe frequencies (< 2000 Hz) was available for assessing middle ear RF (Hunter & Sanford, 2014). Pressurized WAI, however, overcomes this limitation by measuring absorbance, as a function of varying air pressure, over a wide range of frequencies. Polat, Baş, Hayır, Bulut and

Ataş (2015), using pressurized WAI, found the mean RF of 110 Turkish individuals to be 964.7 Hz (SD = 233.94).

An increase in the stiffness of the middle ear system increases the RF, whereas an increase in mass decreases the RF (Shanks, 1984). Although the normative range of the RF of the middle ear is fairly broad, there is potential value in comparing the RF of pathological ears, such as SSCD, to those of normal ears. Such a comparison could provide information on whether the pathology is mass-dominated (presenting with a lower RF) or stiffness-dominated (presenting with a higher RF) (Hunter & Sanford, 2014). Demir et al. (2019) reported a significantly lower mean RF of 548.7 Hz in SSCD ears, compared to those of healthy ears (935.1 Hz), suggesting SSCD to be a mass-dominating pathology. This finding raises the question of whether a reduced RF can be used as a diagnostic indicator for the presence of SSCD, especially when a differential diagnosis is required between SSCD and another pathology, such as otosclerosis, which is generally regarded as stiffness-dominated. Merchant et al. (2015) suggested that a shift in the middle ear RF, due to a change in the total stiffness of the middle and inner ear, may contribute to the occurrence of a PR notch in SSCD ears.

Since the wideband tympanometry component of WAI makes use of dynamic pressure sweeps, the extraction of single-frequency tympanograms which resemble the shape of single-frequency tympanometry measurements is made possible by reducing absorbance as a function of air pressure (Liu et al., 2008; Sanford, Hunter, Feeney, & Nakajima, 2013). The tympanometric component expressed as compliance in the raw data of this study, has been referred to as admittance magnitude (AM) in literature (Liu et al., 2008; Sanford et al., 2013). According to Shanks (1984), a probe frequency close to the RF should be sensitive to changes both in mass and stiffness and therefore, sensitive to all middle ear disease. For this reason there is potential value in comparing the AM at RF of SSCD ears to those of normal ears. At present the researchers are not aware of a similar study that reported the AM at RF of SSCD ears.

Considering the above benefits of using WAI to examine the properties of normal and pathological ears, it was the aim of the current study to describe the absorbance

characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure.

2. CHAPTER TWO: METHODOLOGY

2.1 Research aim

The aim of the study was to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure.

2.2 Research objectives

To support the aim of the study, the following objectives were formulated:

- To determine whether a significant difference in wideband absorbance, measured at ambient pressure, exists at any frequency when comparing ears with confirmed SSCD to ears from a control group.
- To determine whether a significant difference in wideband absorbance, measured at TPP, exists at any frequency when comparing ears with confirmed SSCD to ears from a control group.
- To describe the difference between absorbance measured at TPP and at ambient pressure in confirmed SSCD ears.
- To determine whether a significant difference exists between the RF of the middle ear of the SSCD group and a control group.
- To compare the AM at RF of ears with SSCD to those of ears in a control group.

2.3 Research design

Quantitative data were obtained by means of a cross-sectional descriptive research design. According to Leedy and Ormrod (2019), the term descriptive research encompasses a variety of methodologies that are best suited to examining a situation or event as it currently exists in the world. In a cross-sectional study, the researcher collects all the required data at a single time (Leedy & Ormrod, 2019).

In the current study, the researcher collected WAI data from ears with confirmed SSCD, before corrective surgery, therefore at a specific point in time. The absorbance characteristics of these SSCD ears were described by means of absorbance values at a range of frequencies (226 Hz to 8000 Hz), both at ambient pressure and TPP. For the purpose of statistical analysis, absorbance data from the

initial 122 frequencies were averaged into 1/6th octave frequency bands between 226 and 8000 Hz, using the method used by Feeney et al. (2017). The 1/12 octave frequencies (in Hz) were calculated as $F_{12} = 2^{\frac{[-27;36]}{12}}$ where F_{12} is the reference frequency correlating with a 1/12th octave point (personal communication with Douglas H. Keefe).

2.4 Ethical considerations

Ethical implications should be considered for all research and especially in research where human beings are the focus of the research (Leedy & Ormrod, 2019). The ethical considerations for this research were as follows:

2.4.1 Permission from relevant authorities

- Ethical clearance was obtained from the Ethics Committee of the Faculty of Humanities, University of Pretoria, with reference number HUM025/0319.
- Permission was obtained from the participating otolaryngologist and audiologists who agreed to assist with the study (Appendix A), to access their patient databases and to access the medical records of participants once they provided informed consent.
- Potential participants were contacted by the rooms of the otolaryngologist and audiologists to request whether their contact details can be made available to the researcher.
- Each participant was requested to provide written informed consent to be included as voluntary participants in the current study (Appendix B – SSCD group, and C – control group).

2.4.2 Informed consent

Participants were asked to provide written informed consent (Appendix B & C) before any data was collected. Participation in the study was on a voluntary basis. Participants received verbal and written information on what the study entailed and their rights throughout the research process. This included the right to withdraw from the study at any time. The information was presented in terminology that the participants understood.

2.4.3 Confidentiality

Confidentiality of the participants' identity and personal information was assured. The participants' identity was only known by the researcher. All personal information revealed during the case history interview and testing sessions were kept in strictest confidence. Each participant was assigned an identifying alphanumeric code which was used for all data processing to ensure confidentiality. Coded data will be stored at the Department of Speech-Language Pathology and Audiology, Room 1-5, for a minimum of 15 years according to the University of Pretoria regulations. The results obtained from the current study were reported in the form of a scientific article that was submitted for publication in a peer-reviewed scientific journal, which, together with this dissertation, will be available to professionals in the field of audiology. No identifying information was used at any time. The results of the current study may be used by further researchers.

2.4.4 Avoidance of harm (non-maleficence)

The research did not expose the participants to any physical or emotional harm. The administration of immittance testing occasionally induced mild symptoms of dizziness/vertigo in the SSCD group (participants with SSCD), but this was explained to every participant in the informed consent letter, as well as before commencing the test. There were no financial obligations related to participation in the research to the participants. Participants were offered reimbursement for traveling costs incurred by them for the purpose of data collection according to the rates of the Automobile Association of South Africa.

2.4.5 Honesty

Participants were given access to their own test results as well as to the results of the study. The study was submitted for publishing as an article in a peer-reviewed scientific journal. The study was supervised and reviewed by two supervisors (Prof L. Biagio de Jager and Prof B. Vinck).

2.4.6 Plagiarism

The study and written report of the study are the researchers' own original work. All secondary material cited was acknowledged and referenced according to APA

(seventh edition) referencing guidelines. The study adheres to the University of Pretoria policy on plagiarism. A declaration of originality can be found in Appendix H.

2.4.7 Reliability and validity

Reliability and validity were ensured by the following features of the current study:

- The use of objective testing procedures;
- The use of a control group;
- The use of stringent inclusion criteria for confirmation of SSCD;
- The use of the same testing equipment to obtain research data in all participants;
- The use of instruments that were calibrated according to IEC standards;
- Repetition of each WAI measurement to ensure reliability.

2.4.8 Bias

WAI is an objective test measure and was therefore not influenced by tester or participant bias.

2.5 Participants and participant selection criteria

Twelve participants (14 ears) with confirmed SSCD were tested and ten (12 ears) included in the SSCD group (six female; mean age 48.5 years; SD 12.4) using purposive sampling. Two participants' results were excluded from statistical analysis, because their MEP was found to be more negative than -50 daPa, which was not in accordance with the selection criteria. A control group of 10 participants (12 ears) that matched the SSCD group in terms of age (±2 years) and gender (six female; mean age 48.4 years; SD 12.1) were selected using convenience sampling from acquaintances of the first author. Selection criteria for both groups are described below.

2.5.1 Participant recruitment

2.5.1.1 SSCD group

Names of patients with confirmed SSCD were released by one South African otolaryngologist and three audiologists who agreed to assist with the current study (Appendix A). The patients were contacted by a representative of their rooms to

request whether their details can be made available to the researcher. Only the details of the patients that agreed to have their details shared were revealed to the researcher. These individuals were then contacted by the researcher and the procedure explained to them. Once signed informed consent was received, an appointment was scheduled to verify suitability for the study and to perform selection and research test procedures.

2.5.1.2 Control group

Individuals who matched the SSCD group in terms of age (±2 years) and gender (six female; mean age 48.4 years; SD 12.1) were selected using convenience sampling. They were required to provide written informed consent before any test procedures were conducted.

2.5.2 Participant selection: SSCD group

2.5.2.1 Participant selection criteria: SSCD group

For the current study, participants were required to have been diagnosed with SSCD. Written and verbal competency in English was also required.

Table 2.1 outlines criteria that participants in the SSCD group needed to adhere to, as well as the rationale for their inclusion.

Table 2.1: Inclusion criteria for participants in the SSCD group and rationale for inclusion

Inclusion criteria	Rationale for inclusion
Diagnosed with SSCD by means of high resolution CT imaging.	The use of temporal bone CT images with a slice thickness of less than 1 mm (ideally 0.625 mm or less), with orientation in the plane of the sSCC (Pöschl view) and orthogonal to it (Stenvers view), has been recommended to improve diagnostic accuracy (Ward et al., 2017)
At least one of the following symptoms consistent with SSCD: bone conduction hyperacusis (in the form of autophony, audible eye movements, audible footsteps, etc.), sound-induced vertigo, pressure-induced vertigo, pulsatile tinnitus	Known symptoms of SSCD (Merchant et al., 2015; Minor et al., 1998) Part of criteria for diagnosing SSCD (Ward et al., 2017)
At least one of the following diagnostic tests indicating a third mobile window: low frequency conductive component (including supra-threshold bone conduction values) on behavioural pure tone audiometry; reduced cervical VEMP (cVEMP) thresholds and/or increased ocular VEMP (oVEMP) amplitudes.	An SSCD ear can present with a low frequency conductive component on an air conduction audiogram (Minor, Solomon, Zinreich, & Zee, 1998). Reduced cVEMP thresholds and/or increased oVEMP amplitudes can be indicative of SSCD (Ward et al., 2017; Zuniga, Janky, Nguyen, Welgampola, & Carey, 2013).
No history of significant middle ear disease (otitis media or effusion two or more years previously were not considered significant if there were no known residual consequences).	Middle ear dysfunction affects WAI (Ellison et al., 2012; Merchant et al., 2016; Nakajima et al., 2012, 2013; Sanford & Brockett, 2014; Voss et al., 2012)
No history of otologic surgery.	
Normal tympanic membrane and no excessive cerumen in the ear canal on otoscopy.	Abnormalities of the tympanic membrane might indicate possible middle ear pathology; both middle ear pathology and excessive cerumen or another obstruction in the ear canal could adversely affect WAI results.
Tympanograms at 226 Hz with TPP values between -50 daPa and +50 daPa and static admittance values ≥ 0.3 mmho (BSA, 2013).	Abnormal results on the 226 Hz tympanogram might be indicative of middle ear pathology, which could adversely affect WAI results. Furthermore, normal 226 Hz tympanometry results are generally produced in SSCD ears (Wick et al., 2017).
Present ipsilateral stapedial acoustic reflexes at at least one frequency (500 Hz, 1000 Hz, and 2000 Hz were tested). An ipsilateral reflex was considered “present” if a change in admittance equal to or greater than 0,02 mmho was measured between 70 dB and 90 dB above the behavioural air conduction pure tone threshold at the corresponding frequency (Katz, Chasin, English, & Tillery, 2014). Since the 4000 Hz test frequency is often elevated or absent in ears with normal hearing (Gelfand & Piper, 1984), it was not regarded as a criterion for inclusion.	Ipsilateral reflexes are generally present in SSCD ears (Wick et al., 2017) and present stapedial acoustic reflexes exclude additional middle ear pathology.

Hz: Hertz; TPP: Tympanometric Peak Pressure; daPa: decapascal; mmho: millimho; SSCD: Superior Semicircular Canal Dehiscence; dB: decibel.

2.5.2.2 Material and equipment for participant selection: SSCD group

- A case history (Appendix D) was conducted to rule out previous middle ear pathology and surgery.
- An SSCD questionnaire (Hofmeyr, n.d.) was completed by each participant in the SSCD group (Appendix E) (permission for use granted by Dr L.M. Hofmeyr).
- An otoscopic examination was conducted using a Heine otoscope or Welch Allyn video otoscope.
- Tympanometry and ipsilateral acoustic reflexes were measured using an Interacoustics Titan diagnostic tympanometer, calibrated according to IEC standards. Sanibel ADI mushroom ear tips were used to obtain a seal in the participant's ear canal.

2.5.2.3 Procedure for participant selection: SSCD group

- Each participant that agreed to take part in the study was supplied with an information letter that needed to be signed in order to provide informed consent.
- Existing medical records were studied to obtain audiograms, CT-scan reports and VEMP results. The latest available diagnostic audiogram in the participants' files (administered within a year of data collection) was studied to determine if a conductive component was present in the low frequencies. A cVEMP threshold below 75 dB nHL was regarded a reduced threshold (Zuniga et al., 2013), while high oVEMP amplitudes were defined by norms specific to each clinic.
- The researcher and the participant met at a suitable venue that was mutually agreed upon by the researcher and the participant.
- A case history was conducted to establish the participant's suitability to be included in the SSCD group (Appendix D).
- The participant was requested to complete a questionnaire to establish the extent of the SSCD symptoms (Appendix E).
- An otoscopic examination was conducted on both ears.
- The appropriate size Sanibel ADI mushroom ear tip was selected to obtain a seal in the participant's ear canal while conducting tympanometry and ipsilateral reflex testing.

- Once a seal was obtained, a 226 Hz tympanogram and ipsilateral reflexes were conducted on both ears using a pre-calibrated Interacoustics Titan diagnostic tympanometer.
- The results of all the tests were explained to each participant and they were given the opportunity to ask questions.
- In the event that the above results revealed that the participant was suitable to be included in the SSCD group (as per the inclusion criteria), the researcher continued with data collection.
- In the event that the participant was not suitable to be included in the SSCD group based on the results of the above tests, appropriate information was provided to the participant, including recommendations for treatment if applicable.

Table 2.2 provides an overview of the demographic information and symptoms of the participants in the SSCD group that were obtained through a personal interview and the completion of the SSCD questionnaire (Hofmeyr, n.d.). In the two instances where both ears of a participant were included, each ear's symptoms are outlined.

Table 2.2: SSCD group demographic information and symptoms (n = 12 ears)

No	Gender	Age	Ear	Low frequency conductive component	Confirmed by CT	Reduced cVEMP threshold/ increased oVEMP amplitude	Sound induced dizziness/ vertigo	Pressure induced dizziness/ vertigo	Pressure/ fullness in the ear	Hearing internal sounds (autophony, footsteps, eye movements, breathing)
1	F	57	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	F	50	L	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	M	43	L	Yes	Yes	Not tested	Yes	Yes	Yes	Yes
4	M	43	R	No	Yes	Not tested	Yes	Yes	Yes	Yes
5	F	55	R	Yes	Yes	Not tested	No	Yes	No	Yes
6	M	29	L	Yes	Yes	Not tested	Yes	Yes	Yes	Yes
7	F	42	L	Yes	Yes	Not tested	Yes	Yes	No	Yes
8	F	66	L	Yes	Yes	Yes	Yes	Yes	No	Yes
9	F	66	R	Yes	Yes	Yes	Yes	Yes	Yes	No
10	M	40	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11	F	37	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12	M	66	L	Yes	Yes	Yes	Yes	No	No	No

CT: computed tomography; cVEMP: cervical vestibular evoked myogenic potential; oVEMP: ocular vestibular evoked myogenic potential; M: male; F: female; R: right; L: left.

As outlined in Table 2.2, the majority of participants in the SSCD group had been aware of hearing internal sounds of the body (such as footsteps, eye movements,

breathing), as well as autophony (hearing their own voice as loud or distorted), and the majority also presented with sound and/or pressure induced vertigo.

2.5.3 Participant selection: control group

2.5.3.1 Participant selection criteria: control group

Individuals known to the researcher were requested to participate in the study. Each participant in the control group matched the age (±2 years) and gender (six female; mean age 48.4 years; SD 12.1) of a specific participant in the SSCD group. Written and verbal competency in English was also required. Table 2.3 outlines additional criteria that participants in the control group needed to adhere to, as well as the rationale for their inclusion.

Table 2.3: Inclusion criteria for participants in the control group and rationale for inclusion

Inclusion criteria	Rationale for inclusion
No history of significant middle ear disease (otitis media or effusion two or more years previously were not considered significant if there were no known residual consequences).	Middle ear dysfunction affects WAI (Ellison et al., 2012; Merchant et al., 2016; Nakajima et al., 2012, 2013; Sanford & Brockett, 2014; Voss et al., 2012)
No history of otologic surgery.	
No vestibular symptoms.	General disequilibrium, dizziness and/or vertigo can be symptoms of SSCD (Merchant et al., 2015).
Normal tympanic membrane and no excessive cerumen in the ear canal on otoscopy.	Abnormalities of the tympanic membrane might indicate possible middle ear pathology; both middle ear pathology and excessive cerumen or another obstruction in the ear canal could adversely affect WAI results.
Tympanograms at 226 Hz with TPP values between -50 daPa and +50 daPa and compliance values ≥ 0.3 mmho (BSA, 2013).	Abnormal results on the 226 Hz tympanogram might be indicative of middle ear pathology, which could adversely affect WAI results.
Present ipsilateral stapedial acoustic reflexes at at least one frequency (500 Hz, 1000 Hz, and 2000 Hz were tested). An ipsilateral reflex was considered “present” if a change in admittance equal to or greater than 0,02 mmho was measured between 70 dB and 90 dB above the behavioural air conduction pure tone threshold at the corresponding frequency (Katz et al., 2014). Since the 4000 Hz test frequency is often elevated or absent in ears with normal hearing (Gelfand & Piper, 1984), it was not regarded as criterion for inclusion.	Present stapedial acoustic reflexes exclude additional middle ear pathology.
Pure tone average (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) on audiometry of 25 dB HL or better.	(NIOSH, 1998)
Air-bone gaps no greater than 15 dB at 250 Hz and 10 dB for 500 Hz to 4000 Hz.	The presence of a conductive component on the audiogram might be indicative of middle ear pathology which could adversely affect WAI results. According to Katz et al. (2014), an air-bone gap needs to exceed 10 dB before it is considered significant.

Hz: Hertz; TPP: Tympanometric Peak Pressure; daPa: decapascal; mmho: millimho; SSCD: Superior Semicircular Canal Dehiscence; dB: decibel.

2.5.3.2 Material and equipment for participant selection: control group

- A case history (Appendix D) was conducted to rule out previous middle ear pathology and surgery.
- Otoscopic examination was conducted using a Heine otoscope or Welch Allyn video otoscope
- Tympanometry and ipsilateral acoustic reflexes were measured using an Interacoustics Titan diagnostic tympanometer, calibrated according to IEC

standards. Sanibel ADI mushroom ear tips were used to obtain a seal in the participant's ear canal.

- Pure tone audiometry was conducted in a sound proof room with a diagnostic audiometer that was calibrated by means of IEC standards.

2.5.3.3 Procedure for participant selection: control group

- The test procedure and ethical considerations such as confidentiality were explained to each participant.
- Each participant was provided with an information form which needed to be signed in order to provide informed consent.
- The researcher and the participant met at a private audiology practice in Kempton Park, Gauteng or another suitable venue.
- A case history was conducted to establish the participant's suitability to be included in the control group (Appendix D).
- An otoscopic examination was conducted on both ears.
- The appropriate size Sanibel ADI mushroom ear tip was selected to obtain a seal in the participant's ear canal while conducting tympanometry and ipsilateral reflex testing.
- Once a seal was obtained, a 226 Hz tympanogram and ipsilateral reflexes were conducted on both ears using a pre-calibrated Interacoustics Titan diagnostic tympanometer.
- A pure tone air and bone conduction audiogram was conducted using an Interacoustics AD229b audiometer with a supra-aural TDH39 headset and B71W bone conductor calibrated to IEC standards. The participant was seated in a sound proof room during testing. Pure tone thresholds were determined at octave frequencies from 250 Hz to 8000 Hz for air conduction, and 250 Hz to 4000 Hz for bone conduction.
- The results of all the tests were explained to each participant and they were given the opportunity to ask questions.
- In the event that the above results revealed that the participant was suitable to be included in the control group (as per the inclusion criteria above), the researcher continued with data collection as outlined below.
- In the event that the participant was not suitable to be included in the control group based on the results of the above tests, appropriate information was

provided to the participant, including recommendations for treatment if applicable.

2.5.4 Equipment, procedure and protocol for data collection

2.5.4.1 Equipment for data collection

The test- and recording parameters for WAI listed in Table 2.4 were used for all measurements throughout the study.

Table 2.4: WAI parameters for data collection

Wideband Acoustic Immittance Test Parameters	
Model	Interacoustics Titan Suite Version 3.4.0 (IMP440)
Calibration standards	IEC 60645-5
Frequency range	226 Hz – 8000 Hz broadband stimulus, 21.5/sec.
Intensity	Adult: 100 dB peSPL (100 dB peSPL ≈ 65 dB nHL)
Pressure direction	Positive (200 daPa) to negative (-300 daPa)
Pump speed	Medium
Average wideband frequency range	375 – 2000 Hz (adult)
Probe tips	Sanibel ADI mushroom ear tips

Hz: Hertz; sec: second; peSPL: Peak Equivalent Sound Pressure Level; nHL: Normal Hearing Level; daPa: decapascal.

2.5.4.2 Procedure for data collection

- Each participant that met the selection criteria for inclusion in the control group or the experimental group was asked to continue with data collection at the same venue on the same day. Participants that did not meet the selection criteria were referred to an appropriate medical professional according to their reason for exclusion.
- A unique alphanumeric code was assigned to each suitable participant in order to ensure confidentiality.
- The testing procedure was explained to the participant.
- The appropriate size Sanibel ADI mushroom ear tip was selected to obtain a seal in the participant's ear canal on the ear with confirmed SSCD (in the case of unilateral SSCD) while conducting WAI testing. In the case of bilateral SSCD and for the control group, the left ear was selected as first test ear for every participant with an even alphanumeric code, and the right ear for those with uneven codes.

- Once a seal was obtained, a wideband tympanogram (pressurized from 200 daPa to -300 daPa) was conducted with a pre-calibrated Interacoustics Titan diagnostic tympanometer. The probe remained in the ear canal and the test was repeated twice (resulting in three tests) to ensure reliability.
- The above procedure was repeated for the contralateral ear in the case of bilateral SSCD. For the control group, the procedure was conducted on both ears. For statistical analysis, the same ear as that of the age-matched SSCD participant was included, providing that the selection criteria for that ear were met.
- The results of the tests were explained to each participant and they were given the opportunity to ask questions.
- Absorbance results at ambient pressure as well as at TPP were derived from the pressurized test. Results were exported to Microsoft Excel for analysis from the Titan software using the Titan wideband research module.

2.6 Data analysis

The Stata 15 statistical program was used for statistical analysis (StataCorp, 2015). WAI absorbance results from 226 to 8000 Hz as well as the RF and tympanometric data of each participant were analysed using descriptive statistics, in order to determine the mean, standard deviation (SD), median and interquartile ranges of the data. Inferential statistics were used to determine whether statistical differences existed for the absorbance values at each of the averaged frequencies, the RF and tympanometric data between the SSCD and control groups. Before inferential analysis commenced, data were tested by means of a Skewness and Kurtosis test for normality. Since absorbance data were considered normally distributed ($z<1.96$), the *t*-test method ($\alpha=0.05$) was used to compare absorbance levels of the SSCD group to those of the control group at both ambient pressure and TPP. AM data at 226 Hz and at RF were not normally distributed ($z>1.96$), therefore a Wilcoxon test for comparison of ranked medians were used to compare the AM and RF values of the SSCD group to those of the control group.

3. CHAPTER THREE: RESEARCH ARTICLE

Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence

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Journal: Auris Nasus Larynx

First submission: 9 November 2020 (Appendix G)

3.1 Abstract

Objective: The apparent effect of superior semicircular canal dehiscence (SSCD) on middle ear- and cochlear impedance has led researchers to investigate the use of wideband acoustic immittance when SSCD is suspected. The purpose of the study was to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at tympanometric peak pressure (TPP) and at ambient pressure.

Methods: Wideband Acoustic Immittance was performed at ambient pressure and at TPP on ten participants (12 ears) with confirmed SSCD, as well as on an age- and gender matched control group (12 ears). Inferential statistics were used to determine whether statistical differences existed for the absorbance values at each of the averaged frequencies, the resonance frequency (RF) and tympanometric data between the SSCD and control groups.

Results: The mean absorbance of the SSCD group reached a maximum at 890.9 Hz and a minimum at 6349.6 Hz. When testing absorbance at TPP pressure, a statistically significant increase/peak in the absorbance values of the SSCD group (compared to those of the control group) was found from 630 to 890.9 Hz and a decrease from 4489.8 to 6349.6 Hz. Similar patterns were observed for absorbance at ambient pressure. A lower mean RF for ears with SSCD as well as an increased mean admittance magnitude (AM) value at RF was found compared to that of the control group.

Conclusion: The peak in absorbance around 890 Hz that was found on SSCD ears in the current study is similar to findings from earlier studies that found a peak in

absorbance/notch in reflectance around 1000 Hz, reiterating its use as a screening tool when SSCD is suspected. No significant difference was found between absorbance measured at ambient pressure and at TPP in the current study; however, the stringent inclusion criteria with regard to TPP most likely affected this outcome. As a result of the significant difference in RF of SSCD ears compared to the RF of the control group, the potential value of measuring the RF of the middle ear to differentiate between mass-and stiffness dominated pathologies was also illustrated. Further research measuring the AM at RF in normal and pathological ears was suggested for comparison to the current study and to determine its clinical value.

Keywords: Superior semicircular canal dehiscence, wideband acoustic immittance, wideband tympanometry, wideband absorbance, resonance frequency, admittance magnitude.

3.2 Introduction

Superior Semicircular Canal Dehiscence (SSCD), first described by Minor, Solomon, Zinreich and Zee (1998), is still considered by many as the great otologic mimicker of other diseases, such as otosclerosis and perilymph fistula (Merchant et al., 2015). In many cases, incorrect diagnosis leads to unnecessary explorative surgery or unresolved symptoms. Tavassolie, Penninger, Zuniga, Minor and Carey (2012) cautioned that computed tomography (CT) scans should not be taken as the sole evidence of SSCD, but that the findings should be considered in the context of the patient's symptoms and results of other tests such as the audiogram, vestibular evoked myogenic potential (VEMP) testing, acoustic reflexes, electrocochleography and observation of nystagmus in response to pressure or sound changes. Merchant et al. (2015) suggested that an inexpensive and quick test that would support the need for a CT-scan would be of great value, since VEMP testing has not been standardized across clinics, and together with ECochG are not always readily available. Furthermore, acoustic reflexes are sometimes absent in individuals with normally functioning middle ear systems.

The apparent effect of SSCD on middle ear- and cochlear impedance has led researchers to investigate the use of Wideband Acoustic Immittance (WAI) in the assessment of SSCD (Demir et al., 2019; Merchant et al., 2016, 2015; Nakajima et

al., 2012). Wideband power reflectance (PR) or its compliment, energy absorbance (1 - PR), a component of WAI, provides a broad spectrum measure of the impedance mismatch between the ear canal and middle ear (Withnell, Parent, Jeng, & Allen, 2009). In a study by Nakajima et al. (2012), PR was measured on 11 adult ears with confirmed SSCD. The results demonstrated a notch/decrease in PR (or a peak/increase in absorbance level) around 1000 Hz. Merchant et al. (2015) investigated whether PR measurements coupled with a detection algorithm sensitive to specific SSCD features, could act as a SSCD screening test. Results once again showed that ears with SSCD generally exhibited a notch near 1000 Hz in the PR curves, thereby supporting the findings of Nakajima et al. (2012). In a subsequent study Merchant, Merchant, Rosowski and Nakajima (2016) manipulated human cadaveric temporal bones to simulate SSCD and other middle ear pathologies. PR test results were consistent with those found in adult patient populations (Merchant et al., 2015; Nakajima et al., 2012), with SSCD producing notches in PR near 1000 Hz.

In the aforementioned studies that explored the effect of SSCD on WAI (Merchant et al., 2016, 2015; Nakajima et al., 2012), measurements were predominantly performed at ambient pressure. A more recent study by Demir et al. (2019) investigated whether wideband tympanometry can be used as a screening test for SSCD. Although pressurized measurements were performed, results in this study were reported on absorbance values measured at ambient pressure (Demir et al., 2019).

Several research studies have suggested that measuring absorbance at tympanometric peak pressure (TPP) would allow for a determination of the functional status of the middle ear that would not be compromised by middle ear pressure (MEP) effects (Feeney et al., 2003; Margolis et al., 2001, 1999; Shaver & Sun, 2013). Measuring WAI at TPP is of particular importance in SSCD, taking into account that the effect of SSCD on reflectance/absorbance occurs predominantly in the region of 1000 Hz (Merchant et al., 2016, 2015; Nakajima et al., 2012). Margolis et al. (2001), referring to a study on normal hearing adults (Margolis et al., 1999), mentioned that pressurizing the ear canal increases reflectance for frequencies below 4000 Hz, and causes a decrease in reflectance in the 4000-8000 Hz region. The largest differences occurred in the 1000-2000 Hz region where pressurizing the

ear produced large increases in reflectance. Margolis et al. (2001) concluded that reflectance results at any single ear-canal pressure (including ambient pressure) do not completely characterize the effects of middle ear pathology. In support hereof, Robinson, Thompson and Allen (2016) reported that the power absorbance level is most sensitive to negative MEP from 800 to 1900 Hz. Measuring WAI at TPP would, therefore, aid in further establishing a descriptive absorbance pattern for SSCD ears with the added benefit of eliminating the potential effect of MEP on the absorbance pattern.

Another advantage of measuring WAI at TPP is the ability to extract the resonance frequency (RF) of the middle ear from the results. RF can be defined as the lowest frequency at which the spring (or stiffness) and mass elements of the outer and middle ear structures contribute equally to admittance (Shanks, 1984). Using multi frequency tympanometry, several authors reported the mean resonance of the human middle ear to lie between 800 Hz and 1200 Hz (Shanks, 1984), 990 Hz and 1315 Hz (Margolis & Goycoolea, 1993) and 789 Hz and 1043 Hz (Shahnaz & Polka, 1997), depending on the compensation method used. Polat, Baş, Hayır, Bulut and Ataş (2015) using pressurized WAI, found the mean RF of 110 Turkish individuals to be 964.7 Hz (SD = 233.94). Although the normative range of the RF of the middle ear is fairly broad, comparing the RF of pathological ears, such as SSCD, to those of normal ears could provide information on whether the pathology is mass-dominated (presenting with a lower RF) or stiffness-dominated (presenting with a higher RF) (Hunter & Sanford, 2014). Demir et al. (2019) reported a significantly lower mean RF of 548.7 Hz in SSCD ears, compared to those of healthy ears (935.1 Hz), suggesting SSCD to be a mass-dominating pathology. This finding raises the question of whether a reduced RF can be used as a diagnostic indicator for the presence of SSCD, especially when a differential diagnosis is required between SSCD and another pathology, such as otosclerosis, which is generally regarded as stiffness-dominated. Merchant et al. (2015) suggested that a shift in the middle ear RF, due to a change in the total stiffness of the middle and inner ear, may contribute to the occurrence of a PR notch in SSCD ears.

Since the wideband tympanometry component of WAI makes use of dynamic pressure sweeps, the extraction of single-frequency tympanograms which resemble the shape of single-frequency tympanometry measurements is made possible by

reducing absorbance as a function of air pressure (Liu et al., 2008; Sanford et al., 2013). The tympanometric component expressed as compliance in the raw data of this study, has been referred to as admittance magnitude (AM) in literature (Liu et al., 2008; Sanford et al., 2013). For the purpose of this article, the term AM (in mmho) will be used when referring to compliance. According to Shanks (1984), a probe frequency close to the RF should be sensitive to changes both in mass and stiffness and therefore, sensitive to all middle ear disease. For this reason there is potential value in comparing the AM at RF of SSCD ears to those of normal ears.

Considering the above benefits of using pressurized WAI to examine the properties of normal and pathological ears, it was the aim of this study to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure.

3.3 Materials and methods

Ethical clearance for this study was obtained from the Ethics Committee of the Faculty of Humanities, University of Pretoria, South Africa (reference number HUM025/0319) and each participant provided written informed consent prior to data collection.

3.3.1 Participants

Twelve participants (14 ears) with confirmed SSCD were tested and ten (12 ears) included in the SSCD group (six female; mean age 48.5 years; SD 12.4). Two participants' results were excluded from statistical analysis because their MEP was found to be more negative than -50 daPa, which was not in accordance with the selection criteria. Participants were recruited using purposive sampling – three audiologists and one otolaryngologist in South Africa consented to refer patients with confirmed SSCD to participate in the study, on the condition that potential participants provided written consent for their contact details to be disclosed. Referred participants were included in the study if they met the following criteria (Ward et al., 2017): (1) diagnosed with SSCD by means of high resolution CT imaging; (2) at least one of the following symptoms consistent with SSCD: bone conduction hyperacusis (in the form of autophony, audible eye movements, audible footsteps, etc.), sound-induced vertigo, pressure-induced vertigo, pulsatile tinnitus;

(3) at least one of the following diagnostic tests indicating a third mobile window: low frequency conductive component (including supra-threshold bone conduction values) on behavioural pure tone audiometry; reduced cervical VEMP (cVEMP) thresholds and/or increased ocular VEMP (oVEMP) amplitudes (Ward et al., 2017; Zuniga et al., 2013). Existing medical records were studied to obtain audiograms, CT-scan reports and VEMP results. The most recent diagnostic audiogram in the participants' files (administered within a year of data collection) was studied to determine if a conductive component was present in the low frequencies. A cVEMP threshold below 75 dB nHL was regarded a reduced threshold (Zuniga et al., 2013), while high oVEMP amplitudes were defined by norms specific to each clinic. In addition, participants in the SSCD group had to adhere to the following criteria: (4) no history of significant middle ear disease or otologic surgery; (5) no visible abnormalities on the tympanic membrane and no excessive cerumen in the ear canal on otoscopy; (6) tympanograms at 226 Hz with TPP values between -50 and +50 daPa and static admittance values ≥ 0.3 mmho (BSA, 2013); (7) present ipsilateral stapedial acoustic reflexes at 500, 1000 or 2000 Hz (Hunter & Sanford, 2014). Table 3.1 provides an overview of the demographic information and symptoms of the participants in the SSCD group that were obtained through a personal interview. In the two instances where both ears of a participant were included, each ear's symptoms are outlined.

Table 3.1: SSCD group demographic information and symptoms (n = 12 ears)

No	Gender	Age	Ear	Low frequency conductive component	Confirmed by CT	Reduced cVEMP threshold/ increased oVEMP amplitude	Sound induced dizziness/ vertigo	Pressure induced dizziness/ vertigo	Pressure/ fullness in the ear	Hearing internal sounds (autophony, footsteps, eye movements, breathing)
1	F	57	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
2	F	50	L	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	M	43	L	Yes	Yes	Not tested	Yes	Yes	Yes	Yes
4	M	43	R	No	Yes	Not tested	Yes	Yes	Yes	Yes
5	F	55	R	Yes	Yes	Not tested	No	Yes	No	Yes
6	M	29	L	Yes	Yes	Not tested	Yes	Yes	Yes	Yes
7	F	42	L	Yes	Yes	Not tested	Yes	Yes	No	Yes
8	F	66	L	Yes	Yes	Yes	Yes	Yes	No	Yes
9	F	66	R	Yes	Yes	Yes	Yes	Yes	Yes	No
10	M	40	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
11	F	37	R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
12	M	66	L	Yes	Yes	Yes	Yes	No	No	No

CT: computed tomography; cVEMP: cervical vestibular evoked myogenic potential; oVEMP: ocular vestibular evoked myogenic potential;M: male; F: female; R: right; L: left.

As outlined in Table 3.1, the majority of participants in the SSCD group had been aware of hearing internal sounds of the body (such as autophony, footsteps, eye movements and breathing), and the majority also presented with sound and/or pressure induced vertigo.

A control group of 10 participants (12 ears) that matched the SSCD group in terms of age (±2 years) and gender (six female; mean age 48.4 years; SD 12.1) were selected using purposive sampling from healthy volunteers. The inclusion criteria for participants in the control group were the same as point 4 to 7 of the SSCD group, but also included: (1) air-bone gaps no greater than 15 dB at 250 Hz and 10 dB for 500 to 4000 Hz (Hunter & Sanford, 2014); (2) no vestibular symptoms (Merchant et al., 2015); (3) Pure tone average (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz) on audiometry of 25 dB HL or better (NIOSH, 1998).

3.3.2 Equipment

Tympanometry at 226 Hz and WAI measurements were performed using an Interacoustics Titan diagnostic tympanometer (Suite version 3.4.0), calibrated according to IEC 60645-5IEC standards prior to commencement of data collection. Sanibel ADI mushroom ear tips were used to obtain a seal in the ear canal. Broadband stimuli from 226 to 8000 Hz were presented at a rate of 21.5/sec. and an intensity of 100 dB peSPL. Pressure direction was positive (200 daPa) to negative (-300 daPa), with a medium pump speed. Pure tone audiometry on the control group participants was conducted with a diagnostic audiometer that was calibrated by means of IEC standards.

3.3.3 Procedures

A medical history was obtained from each participant to obtain information regarding hearing loss, middle ear conditions, otologic surgery, history of vertigo and/or dizziness, tinnitus, noise exposure, and family history of hearing loss, as well as their general medical condition and medication used. Participants in the SSCD group were also asked more detailed questions regarding symptoms specific to SSCD, such as hearing internal sounds of the body (autophony, audible eye movements, audible footsteps, etc.), sound-induced vertigo, pressure-induced vertigo, and pulsatile tinnitus. An otoscopic evaluation as well as 226 Hz tympanometry and

ipsilateral acoustic stapedial reflex testing were conducted on each participant. Participants in the control group also underwent air- and bone conduction behavioural pure tone threshold testing (with an Interacoustics AD226b audiometer) in order to rule out a conductive component. SSCD group participants' most recent audiograms were obtained from their treating ENT/audiologist to determine whether a conductive component was present in the lower frequencies.

Wideband acoustic immittance testing was subsequently performed on participants that met the inclusion criteria. Once an acoustic seal was obtained in the ear canal (indicated on the software), a pressurized absorbance test was performed three consecutive times without removing the probe from the ear canal. Absorbance at ambient pressure was derived from the pressurized test, and both the ambient and TPP results were exported to an Excel file via MATLAB using the Interacoustics Titan Wideband Research Module. Absorbance data from the three tests were averaged for each condition (ambient and TPP) and each participant. For the purpose of statistical analysis, absorbance data from the initial 122 frequencies were averaged into 1/6th octave frequency bands between 226 and 8000 Hz, using the method used by Feeney et al. (Feeney et al., 2017). The 1/12 octave frequencies (in Hz) were calculated as $F_{12} = 2^{\frac{[-27;36]}{12}}$ where F_{12} is the reference frequency correlating with a 1/12th octave point (personal communication with Douglas H. Keefe).

The RF (in Hz) of each participant, as well as the AM (in mmho), gradient (in daPa), peak pressure (in daPa) and equivalent ear canal volume (in ml), both at 226 Hz and at RF (comprising the tympanometric data), were also extracted from the pressurized WAI test for statistical analysis and exported to an Excel spreadsheet.

3.3.4 Statistical Analysis

The Stata 15 statistical program was used for statistical analysis (StataCorp, 2015). WAI absorbance results from 226 to 8000 Hz as well as the RF and tympanometric data of each participant were analysed using descriptive statistics, in order to determine the mean, standard deviation, median, and interquartile ranges of the data. Inferential statistics were used to determine whether statistical differences existed for the absorbance values at each of the averaged frequencies, the RF, and tympanometric data between the SSCD and control groups. Before inferential

analysis commenced, data were tested by means of a Skewness and Kurtosis test for normality. Since absorbance data were considered normally distributed (z<1.96), the t-test method (α=0.05) was used to compare absorbance levels of the SSCD group to those of the control group at both ambient pressure and TPP. AM data at 226 Hz and at RF were not normally distributed (z>1.96), therefore a Wilcoxon test for comparison of ranked medians were used to compare the AM and RF values of the SSCD group to those of the control group. The following section presents the research results based on the aims of the study.

3.4 Results

3.4.1 Wideband absorbance at ambient pressure

Figure 1 illustrates the mean absorbance values ±1 SD of the SSCD group from 226 to 8000 Hz, overlaid on the mean absorbance ±1 SD of the control group measured at ambient pressure.

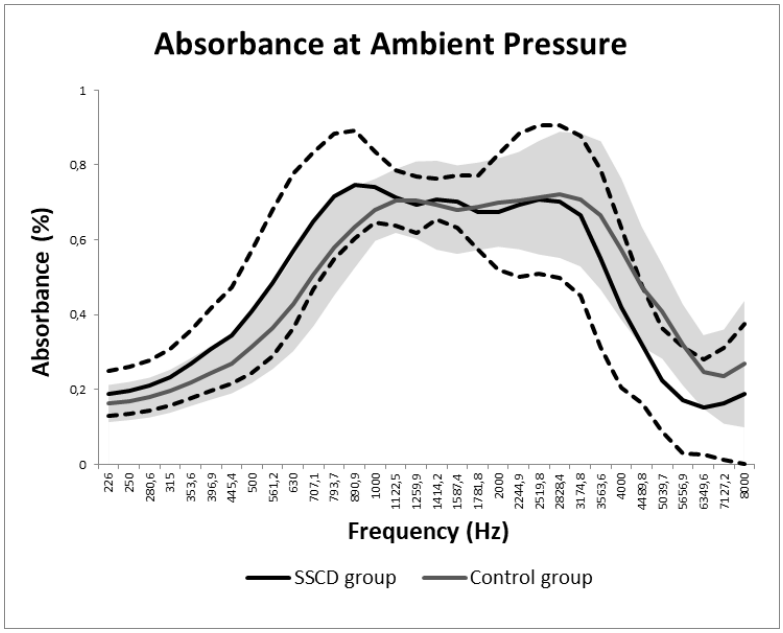

Figure 1: Absorbance mean (solid line) and standard deviation (black dotted lines) of superior semicircular canal dehiscence (SSCD) group and mean (grey solid line) and standard deviation (grey shaded area) of control group measured at ambient pressure.
Hz: Hertz.

As illustrated in Figure 1, a distinct peak in mean absorbance of the SSCD group is visible just below 1000 Hz with the absorbance mean reaching a maximum at 890.9 Hz, and remaining within 0.06% of the maximum level up to 2828.4 Hz, where it starts to decline to a minimum level at 6349.6 Hz. The mean absorbance of the control group follows a similar pattern, but with absorbance mean at least 1 SD

below the mean of the SSCD group between 500 Hz and 1000 Hz, reaching its maximum only at 2828.4 Hz, and mean absorbance values at least 1 SD above the mean of the SSCD group between 5039.7 and 6349.6 Hz.

To assess the difference in absorbance between the SSCD and control groups, a *t*-test was conducted (α=0.05). Table 3.2 displays the results of the *t*-test, as well as the mean and SD of absorbance measured at ambient pressure at each frequency.

As displayed in Table 3.2, the following frequency ranges showed a statistical significant difference (α=0.05) in absorbance at ambient pressure between the SSCD and control groups: 707.1 to 890.9 Hz ($t(22) = -2.25$ to -2.17; $p = 0.041$, 0.035, 0.040), indicating greater absorbance values for the SSCD group than the control group in this range, while at 4489.8 to 5656.9 Hz statistically significantly lower absorbance values were found for the SSCD group than for the control group ($t(22) = 2.39$ to 3.39; $p = 0.026$, 0.003, 0.009). If the cut-off *p*-value for significant differences is lowered to 0.01 to compensate for the use of multiple comparisons, only 5039.7 and 5656.9 Hz show a significant difference. With this correction applied, the remaining frequencies with a *p*-value below 0.05 can be regarded as trends.

Table 3.2: Absorbance mean and standard deviation for superior semicircular canal dehiscence (n=12 ears) and control (n=12 ears) groups at ambient pressure; as well as the t- and p-values for each frequency resulting from inferential statistics to determine difference between groups (α=0.05). Statistically significant p-values are marked with an asterisk.

Frequency (Hz)	SSCD group absorbance Mean ± SD (%)	Control group absorbance Mean ± SD (%)	*t*-value (*df*=22)	*p*-value
226.0	0.19 ±0.06	0.16 ±0.05	-1.18	0.250
250.0	0.20 ±0.06	0.17 ±0.05	-1.22	0.234
280.6	0.21 ±0.07	0.18 ±0.05	-1.27	0.218
315.0	0.23 ±0.08	0.20 ±0.06	-1.36	0.186
353.6	0.27 ±0.09	0.22 ±0.06	-1.52	0.142
396.9	0.31 ±0.11	0.24 ±0.07	-1.65	0.113
445.4	0.34 ±0.13	0.27 ±0.08	-1.71	0.102
500.0	0.41 ±0.16	0.31 ±0.09	-1.76	0.092
561.2	0.49 ±0.20	0.36 ±0.11	-1.87	0.074
630.0	0.57 ±0.21	0.43 ±0.13	-2.02	0.055
707.1	0.65 ±0.18	0.51 ±0.14	-2.17	0.041*
793.7	0.72 ±0.17	0.58 ±0.13	-2.25	0.035*
890.9	0.75 ±0.14	0.63 ±0.11	-2.19	0.040*
1000.0	0.74 ±0.09	0.68 ±0.08	-1.70	0.104
1122.5	0.71 ±0.07	0.70 ±0.09	-0.25	0.807
1259.9	0.69 ±0.08	0.71 ±0.10	0.36	0.720
1414.2	0.71 ±0.05	0.69 ±0.12	-0.40	0.690
1587.4	0.70 ±0.07	0.68 ±0.12	-0.52	0.610
1781.8	0.67 ±0.10	0.69 ±0.12	0.36	0.722
2000.0	0.67 ±0.15	0.70 ±0.12	0.46	0.647
2244.9	0.69 ±0.19	0.71 ±0.13	0.18	0.853
2519.8	0.71 ±0.20	0.71 ±0.15	0.07	0.942
2828.4	0.70 ±0.20	0.72 ±0.17	0.24	0.815
3174.8	0.67 ±0.21	0.71 ±0.18	0.52	0.610
3563.6	0.55 ±0.24	0.67 ±0.20	1.28	0.214
4000.0	0.42 ±0.21	0.58 ±0.19	1.89	0.072
4489.8	0.32 ±0.16	0.47 ±0.16	2.39	0.026*
5039.7	0.23 ±0.14	0.41 ±0.13	3.39	0.003*
5656.9	0.17 ±0.14	0.32 ±0.11	2.85	0.009*
6349.6	0.15 ±0.13	0.25 ±0.10	2.05	0.053
7127.2	0.16 ±0.15	0.23 ±0.13	1.27	0.216
8000.0	0.19 ±0.19	0.27 ±0.17	1.10	0.285

SSCD: superior semicircular canal dehiscence; SD: standard deviation; Hz: Hertz.

3.4.2 Wideband absorbance at TPP

Figure 2 illustrates the mean absorbance values ±1 SD of the SSCD group from 226 to 8000 Hz, overlaid on the mean absorbance ±1 SD of the control group measured at TPP.

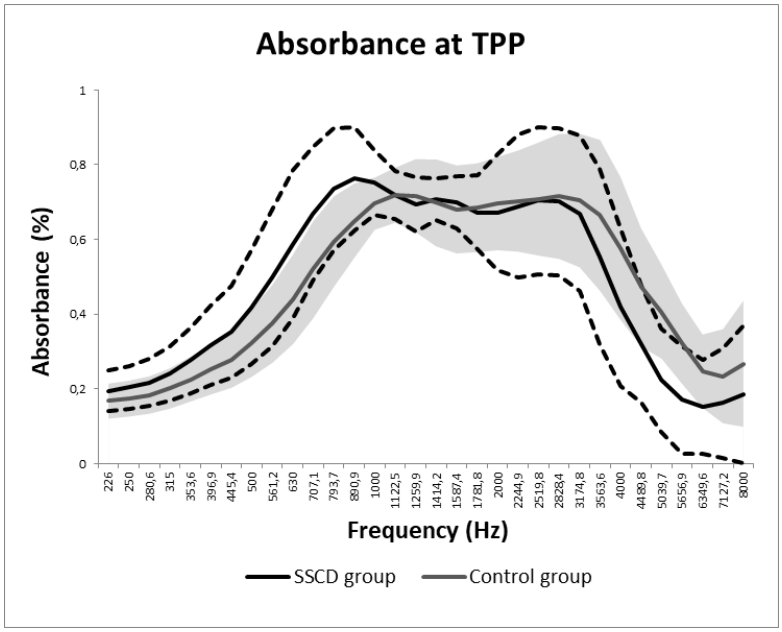

Figure 2: Absorbance mean (solid line) and standard deviation (black dotted lines) of superior semicircular canal dehiscence (SSCD) group and mean (grey solid line) and standard deviation (grey shaded area) of control group measured at tympanometric peak pressure.
Hz: Hertz.

As can be seen in Figure 2, the shape of the absorbance curves of the SSCD group as well as the control group is similar to that displayed in Figure 1. Once again the absorbance mean of the control group was at least 1 SD below the mean of the SSCD group between 500 Hz and 1000 Hz, and at least 1 SD above the mean of the SSCD group between 5039.7 and 6349.6 Hz. .

As was the case with absorbance at ambient pressure, a *t*-test was conducted (α=0.05) to assess the difference in absorbance between the SSCD and control groups when testing at TPP. Table 3.3 displays the results of the *t*-test, as well as the mean and standard deviation of absorbance measured at TPP for the SSCD and control groups.

Table 3.3: Absorbance mean and standard deviation for superior semicircular canal dehiscence (n=12 ears) and control groups (n=12 ears) at tympanometric peak pressure; as well as the t- and p-values for each frequency from inferential statistics to determine difference between groups (α=0.05). Statistically significant p-values are marked with an asterisk.

Frequency (Hz)	SSCD group absorbance Mean ± SD (%)	Control group absorbance Mean ± SD (%)	*t*-value (*df*=22)	*p*-value
226.0	0.20 ±0.06	0.17 ±0.05	-1.33	0.196
250.0	0.20 ±0.06	0.17 ±0.05	-1.37	0.184
280.6	0.22 ±0.06	0.18 ±0.05	-1.41	0.171
315.0	0.24 ±0.07	0.20 ±0.05	-1.51	0.146
353.6	0.28 ±0.09	0.23 ±0.06	-1.66	0.112
396.9	0.32 ±0.11	0.25 ±0.07	-1.78	0.088
445.4	0.35 ±0.12	0.28 ±0.07	-1.83	0.081
500.0	0.42 ±0.15	0.32 ±0.09	-1.89	0.072
561.2	0.50 ±0.18	0.37 ±0.10	-2.02	0.055
630.0	0.59 ±0.20	0.44 ±0.12	-2.21	0.038*
707.1	0.67 ±0.18	0.52 ±0.13	-2.36	0.027*
793.7	0.73 ±0.16	0.59 ±0.12	-2.40	0.025*
890.9	0.76 ±0.14	0.65 ±0.10	-2.30	0.032*
1000.0	0.75 ±0.09	0.70 ±0.07	-1.79	0.087
1122.5	0.72 ±0.07	0.72 ±0.07	-0.01	0.991
1259.9	0.69 ±0.07	0.72 ±0.10	0.65	0.524
1414.2	0.71 ±0.06	0.70 ±0.12	-0.24	0.811
1587.4	0.70 ±0.07	0.68 ±0.12	-0.49	0.628
1781.8	0.67 ±0.10	0.69 ±0.12	0.28	0.785
2000.0	0.67 ±0.15	0.70 ±0.12	0.41	0.688
2244.9	0.69 ±0.19	0.70 ±0.14	0.20	0.843
2519.8	0.70 ±0.20	0.71 ±0.15	0.06	0.952
2828.4	0.70 ±0.20	0.72 ±0.17	0.19	0.850
3174.8	0.67 ±0.21	0.70 ±0.18	0.45	0.658
3563.6	0.55 ±0.23	0.66 ±0.20	1.23	0.231
4000.0	0.42 ±0.21	0.58 ±0.19	1.90	0.070
4489.8	0.32 ±0.16	0.47 ±0.16	2.39	0.026*
5039.7	0.22 ±0.14	0.41 ±0.13	3.40	0.003*
5656.9	0.17 ±0.14	0.32 ±0.11	2.92	0.008*
6349.6	0.15 ±0.13	0.25 ±0.10	2.08	0.050*
7127.2	0.16 ±0.15	0.23 ±0.13	1.30	0.210
8000.0	0.19 ±0.18	0.27 ±0.17	1.13	0.273

SSCD: superior semicircular canal dehiscence; SD: standard deviation; Hz: Hertz.

As displayed in Table 3.3, the following frequency ranges showed a statistical significant difference in absorbance at TPP between the SSCD and control groups: 630 to 890.9 Hz ($t(22)$ = -2.40 to -2.21; p = 0.038, 0.027, 0.025, 0.032), indicating greater absorbance values for the SSCD group than the control group in this range, while statistically lower absorbance values were measured for the SSCD group compared to the control group at 4489.8 to 6349.6 Hz ($t(22)$ = 2.08 to 3.40; p = 0.026, 0.003, 0.008, 0.050). If the cut-off p-value for significant differences is lowered to 0.01 to compensate for the use of multiple comparisons, once again only 5039.7 and 5656.9 Hz show a significant difference, with the remaining frequencies with a p-value below 0.05 regarded as trends.

3.4.3 Resonance frequency

The RF of each participant was derived from the absorbance data at TPP by the Titan software. Figure 3 illustrates the mean RF for the SSCD and control groups.

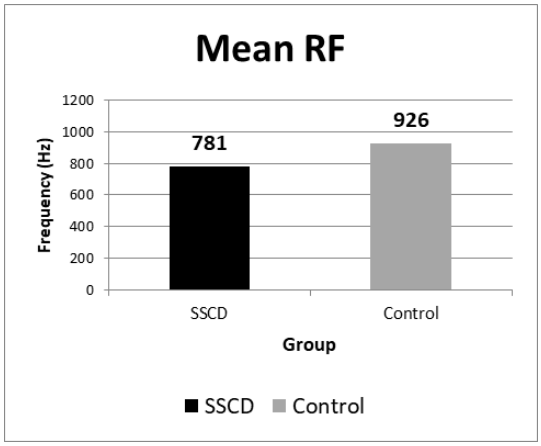

Figure 3: Mean resonance frequency of superior semicircular canal dehiscence and control groups.
SSCD: superior semicircular canal dehiscence; Hz: Hertz.

The mean RF of the SSCD group (n=12 ears) was 780.61 Hz (±169.78), while the mean RF of the control group (n=12 ears) was 926 Hz (±147.71). A t-test showed that the RF of the SSCD group was significantly lower (α=0.05) than the RF of the control group ($t(22)$ = 2.24; p = 0.036).

3.4.4 Admittance magnitude at resonance frequency

The tympanometric values (peak pressure, gradient, AM and volume) at 226 Hz and at RF of the SSCD group and the control group, as derived from the WAI tests, are presented in Table 3.4.

Table 3.4: Tympanometric values at 226 Hz and at resonance frequency for the superior semicircular canal dehiscence (n=12 ears) and control (n=12 ears) groups

	SSCD Group Mean ±SD		Control Group Mean ±SD	
	226 Hz	RF	226 Hz	RF
Peak Pressure (daPa)	-2.47 ±7.48	7.53 ±10.68	-3.75 ±9.60	13.42 ±15.61
Gradient (daPa)	83.83 ±13.36	86.08 ±16.18	94.64 ±18.10	94.03 ±20.28
AM (mmho)	0.94 ±0.43	3.58 ±1.70	0.61 ±0.21	1.95 ±0.61
Volume (ml)	1.21 ±0.35	1.18 ±0.39	1.18 ±0.24	1.18 ±0.24

SSCD: superior semicircular canal dehiscence; Hz: Hertz; RF: resonance frequency; AM: admittance magnitude; daPa: decapascal; ml: millilitre; mmho: millimho.

Of note is the greater mean AM of the RF tympanograms (3.58 mmho) compared to that of the 226 Hz tympanograms (0.94 mmho) in the SSCD group, which is the case only to a lesser extent for the control group (RF mean AM: 1.95 mmho; 226 Hz mean AM: 0.61 mmho). A Wilcoxon test showed a statistical significant difference (α=0.05) between the AM of the SSCD and control groups, both at 226 Hz (z = -2.08; p = 0.038) and at RF (z = -2.571; p = 0.010). A t-test was also conducted to compare the difference between groups of the gradient at 226 Hz and at RF, but no significant difference (α=0.05) was found (gradient at 226 Hz: $t(22)$ = 1.66; p = 0.110; gradient at RF: $t(22)$ = 1.06; p = 0.300).

3.5 Discussion

3.5.1 Absorbance at ambient pressure and at TPP

A distinctive peak in absorbance, both at ambient pressure and at TPP, was found around 890.9 Hz in the SSCD group of the current study. This is in accordance with results from studies by Merchant et al. (2015, 2016) and Nakajima et al. (2012) that reported a notch/decrease in PR (peak/increase in absorbance level) around 1000 Hz in SSCD ears. In the current study, the mean absorbance curves of the SSCD and control groups were also similar to those displayed by Merchant et al. (2015, 2016) and Nakajima et al. (2012). Demir et al. (2019) found a mean maximum absorbance frequency of 1706.3 Hz in their SSCD group; however, they did not report the mean absorbance value at this frequency. It is therefore not clear whether the mean absorbance at the maximum absorbance frequency (1706.3 Hz) reported by Demir et al. (2019) is comparable to the absorbance values around this frequency in the current study. In the current study, absorbance values around 1706.3 Hz were very close to the maximum absorbance reported at 890.9 Hz, only starting to

decrease above 2828.4 Hz. However, in these frequency ranges the absorbance levels of the current study and studies by Merchant et al. (2015) and Nakajima et al. (2012) were comparable to those of the control group, and are therefore not emphasized in the discussion. Since the research objectives of the study by Demir et al. (2019) did not include a description of the absorbance values and curve of SSCD ears, it is also not clear if an increase in absorbance was noted around 1000 Hz in their study. It should further be noted that as part of the selection criteria of their SSCD group, Demir et al. (2019) excluded SSCD ears that exhibited a low frequency conductive component during audiometric testing. This was not the case in the current study or in the studies by Merchant et al. (2015) and Nakajima et al. (2012), while Merchant et al. (2016) manipulated cadaveric preparations in order to simulate SSCD, making audiometric results irrelevant. Since Merchant et al. (2015) reported a significant correlation between the PR notch size and the averaged low frequency air-bone gap on pure tone audiometry, it is possible that omitting SSCD ears with low frequency air-bone gaps could affect absorbance results when compared to studies where such ears were included.

Of interest is that in the current study, a significant decrease in absorbance of the SSCD group at both ambient pressure and TPP was demonstrated in the higher frequencies (4489.8 to 6349.6 Hz), when compared to the control group. While an increase in reflectance in the high frequencies (decrease in absorbance) is visible on the graphical representation of data in studies by Merchant et al. (2015, 2016) and Nakajima et al. (2012), a difference between SSCD and normal ears was not reported for this frequency range. One possible reason for this could be that due to frequency limitations in the WAI device used in these studies, WAI was only performed up to 6000 Hz, as opposed to 8000 Hz in the current study. Demir et al. (2019) did not report the absorbance values of SSCD ears in the higher frequencies. Further research on a larger number of participants with SSCD is required to determine whether the decreased high frequency absorbance pattern is repeated, and to determine whether additional common characteristics such as size or location of dehiscence are affecting the absorbance values in this frequency range.

Although the range of frequencies that exhibited a significant difference when comparing absorbance values of SSCD ears to those of the control group were slightly larger when testing at TPP compared to testing at ambient pressure, a

marked difference in the results of absorbance at ambient pressure and at TPP were not clearly evident. A 3 way repeated measure ANOVA on the absorbance values with group, pressure and frequencies as independent factors, and with pressure and frequencies as repeated factors indicated no significant interaction between pressure and group ($p = 0.99$) or pressure/group/frequency ($p = 1.00$). There was therefore no significant interaction between types of pressure and group on absorbance values at different frequency levels. This similarity in absorbance results measured at ambient pressure and TPP could potentially be attributed to the fact that an MEP of between -50 daPa and 50 daPa were included in the selection criteria of participants, therefore the pressure at which the ambient and TPP tests were administered didn't differ with more than 50 daPa. Further research is required to determine whether a greater difference in absorbance might be observed when testing participants with MEP outside the normative ranges described in literature (BSA, 2013).

The distinctive peak in absorbance around 890.9 Hz that was found in the current study supports the use of WAI testing as a screening test for suspected SSCD. However, a relatively wide normative absorbance range causes the reflectance/ absorbance values around 1000 Hz of SSCD ears to overlap with those of normal ears in some cases (Nakajima et al., 2013). This trend was also observed in the current study. The occurrence of a peak in absorbance around 1000 Hz in ears with a normal audiogram could be the result of a hypermobile TM (Rosowski et al., 2012), while peaks have also been found in ears with ossicular chain discontinuity (OCD) (Farahmand et al., 2016; Karuppannan & Barman, 2020; Nakajima et al., 2012). Furthermore, the peak in absorbance around 890.9 Hz was also not present in every SSCD ear in the current study. Although the peak varied in size, a total of 9 out of the 12 SSCD ears displayed a noticeable peak in absorbance around 890.0 Hz. No obvious pattern of clinical symptoms was reported amongst the three ears that didn't display the peak; therefore other factors such as the size and location of the dehiscence could have had an effect on the presence of a peak, and warrants further investigation. Furthermore, the diagnosis of SSCD ears in the current study had not yet been confirmed surgically, therefore the possibility of false positives cannot be excluded. Therefore it is recommended that WAI results are interpreted in conjunction with clinical symptoms, acoustic reflex results, tuning fork tests (such as the malleolus test), and the audiogram when deciding on further referral for

radiological imaging as well as management once a conclusive diagnosis has been made.

3.5.2 Resonant frequency

The lower mean RF for ears with SSCD compared to that of the control group in the current study, is in agreement with results by Demir et al. (2019) who also found a lower mean RF in their SSCD group compared to healthy ears. The mean RF of the control group in the current study (926 Hz) is similar to the mean RF of the normal group (935.1 Hz) reported by Demir et al. (2019) as well as to the mean RF of normal ears of 964.6 Hz reported by Polat et al. (2015). However, the mean RF of the SSCD group in the study by Demir et al. (2019) of 548.7 Hz (±182.9) was lower than the mean RF of the SSCD group reported in the current study (780.6 Hz ±169.78). Factors such as the size and location of the dehiscence as well as the exclusion of ears with a low frequency component by Demir et al. (2019) might be responsible for this difference. However, the studies were in agreement that a lower mean RF is evident in SSCD compared to normal ears. In general a dehiscence of the sSCC results in increased freedom of stapes motion due to the decrease in the acoustic impedance of the inner ear (Pisano, Niesten, Merchant, & Nakajima, 2012), which could be responsible for a reduction of the stiffness component of the SSCD ear, resulting in a lower RF. A decreased RF compared to those of normal ears, however, is not unique to SSCD. A lower RF was reported in cases of OCD (Karuppannan & Barman, 2020), tympanic membrane perforations (Kim et al., 2019) and enlarged vestibular aqueduct (Sato et al., 2002), while Shanks (1984) listed otitis externa, serous otitis media and tympanic membrane pathology as pathologies that produce a decrease in RF.

For this reason, as well as an overlap of RF values of pathological ears with the RF of healthy ears, the RF in itself cannot be used for diagnostic purposes. However, in cases of unilateral SSCD, a comparison of the RF of the two ears is useful. In the current study, for example, all the participants with unilateral SSCD displayed a lower RF in the SSCD ear than in the non-SSCD ear. Furthermore, the RF as part of a diagnostic test battery could be of potential value in cases where differential diagnosis is required between mass- and stiffness dominated pathologies, especially those that often mimic one another, such as otosclerosis and SSCD.

3.5.3 Admittance magnitude at resonance frequency

Although the AM at 226 Hz of the SSCD ears in the current study was significantly higher than that of the control group (p = 0.038), the mean AM at 226 Hz of the SSCD group (0.94 mmho, ±0.43) was still within the normative range for static admittance at 226 Hz (BSA, 2013). This is in contrast to OCD, where a higher mean AM at 226 Hz in OCD ears of 2.06 mmho (±0.55) was reported by Karuppannan & Barman (2020), who studied the wideband absorbance pattern in adults with otosclerosis and OCD.

Since a probe frequency close to the RF is sensitive to changes both in mass and stiffness, it should be sensitive to all middle ear disease (Shanks, 1984). For this reason the current study reported on the AM as measured at RF, finding the AM at RF of the SSCD group significantly higher (p = 0.010) than that of the control group. However, at this stage no normative data is available for any tympanometric values measured at the RF of the middle ear, and to the knowledge of the authors no previous studies have reported on AM measured at RF for healthy ears, SSCD ears or another pathology. Therefore the results of AM at RF cannot be used for diagnostic purposes in SSCD at present, and further research in this area is recommended to determine its value as part of the test battery.

3.6 Clinical applications

A peak in wideband absorbance at TPP around 890 Hz can be indicative of SSCD. While the results of WAI testing can not necessarily be regarded as superior to those of other tests that are used in the diagnosis of SSCD, it does hold certain advantages such as being quick and largely non-invasive. However, results need to be interpreted alongside clinical symptoms and other tests such as a CT-scan, VEMP testing, and an audiogram. Adding the measurement of the RF to WAI when testing suspected SSCD ears can be of potential use, especially when differentiating between SSCD and stiffness dominated middle ear pathologies, such as otosclerosis, that often mimic one another.

3.7 Limitations of the study and recommendations for future research

- A larger number of SSCD participants in the current study would have been preferable; however, the incidence of SSCD has been reported to be as low as

0.7% of individuals (Carey, Minor, & Nager, 2000). The small sample size limited the complexity of the statistical analyses, since multivariate tools were not suitable for use in such a small sample.

- Because there were multiple comparisons the risk of a type 1 error (false positive) was higher and therefore further research, focusing on fewer comparisons, is recommended.
- Further research on a larger number of participants with SSCD is required to determine whether the decreased high frequency absorbance pattern found in the current study is repeated, and whether additional common characteristics such as size or location of the dehiscence are affecting the absorbance values in this frequency range.
- It would be of interest to compare the WAI absorbance characteristics of SSCD ears pre- and post-corrective surgery, to determine whether the correction reduced the peak in absorbance values around 1000 Hz that was measured pre-surgery.
- The value of WAI results in cases where SSCD was surgically confirmed despite negative VEMP results can also be explored. This would serve to determine whether a peak in absorbance around 1000 Hz could be indicative of SSCD even in the absence of an increase in oVEMP amplitude.
- Future studies may attempt to determine whether a correlation exists between the presence of a characteristic peak in absorbance in SSCD ears, and the reported symptoms, as well as the size of the dehiscence, in an attempt to explain why the peak is not evident in all SSCD ears.
- Lastly, normative data for AM at RF need to be established in order to promote its value in the differential diagnosis of middle ear pathologies.

3.8 Conclusion

It was the aim of this study to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure. Absorbance values measured in SSCD ears showed a peak in absorbance around 890 Hz, similar to findings from earlier studies that found a peak in absorbance/notch in reflectance around 1000 Hz. No significant difference was found between absorbance measured at ambient pressure and at TPP in the current study; however, the stringent inclusion criteria with regard to TPP most likely affected

this outcome. As a result of the significant difference in the RF of SSCD ears compared to the RF of the control group, the potential value of measuring the RF of the middle ear to differentiate between mass-and stiffness dominated pathologies, was also illustrated. Further research measuring the AM at RF in normal and pathological ears was suggested to determine its clinical value.

Ethical approval

Approval for this study was obtained from the Ethics Committee of the Faculty of Humanities, University of Pretoria, South Africa (no. HUM025/0319).

Informed consent

Informed consent was obtained from all participants of the study.

Declaration of interest

The study was conducted in fulfilment of the requirements for a master degree in audiology by the first author. The first author was employed as audiologist by Demant South Africa for a portion of the study.

4. CHAPTER FOUR: SUMMARY AND CONCLUSION

4.1 Summary of results

The apparent effect of SSCD on middle ear- and cochlear impedance has led researchers to investigate the use of wideband acoustic immittance as a screening tool in the assessment of SSCD. Limited research has been conducted to date that described the absorbance characteristics of SSCD ears at TPP. It was therefore the aim of this study to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure. WAI data were collected from ears with confirmed SSCD as well as from those of a control group that matched the SSCD group in terms of age and gender. The wideband absorbance of these SSCD ears were described by means of absorbance values at a range of frequencies (226 to 8000 Hz), both at ambient pressure and TPP. The absorbance characteristics as well as the RF and AM at RF extracted from wideband tympanometry of each participant were analysed to determine whether statistical differences existed between the SSCD and control groups. The following paragraphs provide a summary of the results as it pertains to the aim of the study.

4.1.1 Absorbance at ambient pressure and at TPP

A distinctive peak in absorbance, both at ambient pressure and at TPP, was found around 890.9 Hz in the SSCD group of the current study. This is in accordance with results from studies by Merchant et al. (2015, 2016) and Nakajima et al. (2012) that reported a notch/decrease in PR (peak/increase in absorbance level) around 1000 Hz in SSCD ears. In the current study, the mean absorbance curves of the SSCD and control groups were also similar to those displayed by Merchant et al. (2015, 2016) and Nakajima et al. (2012). Demir et al. (2019) found a mean maximum absorbance frequency of 1706.3 Hz in their SSCD group; however, they did not report the mean absorbance value at this frequency. It is therefore not clear whether the mean absorbance at the maximum absorbance frequency (1706.3 Hz) reported by Demir et al. (2019) is comparable to the absorbance values around this frequency in the current study. In the current study, absorbance values around 1706.3 Hz were very close to the maximum absorbance reported at 890.9 Hz, only starting to decrease above 2828.4 Hz. However, in these frequency ranges the absorbance levels of the current study and studies by Merchant et al. (2015) and Nakajima et al.

(2012) were comparable to those of the control group, and are therefore not emphasized in the discussion. Since the research objectives of the study by Demir et al. (2019) did not include a description of the absorbance values and curve of SSCD ears, it is also not clear if an increase in absorbance was noted around 1000 Hz in their study. It should further be noted that as part of the selection criteria of their SSCD group, Demir et al. (2019) excluded SSCD ears that exhibited a low frequency conductive component during audiometric testing. This was not the case in the current study or in the studies by Merchant et al. (2015) and Nakajima et al. (2012), while Merchant et al. (2016) manipulated cadaveric preparations in order to simulate SSCD, making audiometric results irrelevant. Since Merchant et al. (2015) reported a significant correlation between the PR notch size and the averaged low frequency air-bone gap on pure tone audiometry, it is possible that omitting SSCD ears with low frequency air-bone gaps could affect absorbance results when compared to studies where such ears were included.

Of interest is that in the current study, a significant decrease in absorbance of the SSCD group at both ambient pressure and TPP was demonstrated in the higher frequencies (4489.8 to 6349.6 Hz), when compared to the control group. While an increase in reflectance in the high frequencies (decrease in absorbance) is visible on the graphical representation of data in studies by Merchant et al. (2015, 2016) and Nakajima et al. (2012), a difference between SSCD and normal ears was not reported in this frequency range. One possible reason for this could be that due to frequency limitations in the WAI device used in these studies, WAI was only performed up to 6000 Hz, as opposed to 8000 Hz in the current study. Demir et al. (2019) did not report the absorbance values of SSCD ears in the higher frequencies. Further research on a larger number of participants with SSCD is required to determine whether the decreased high frequency absorbance pattern is repeated, and to determine whether additional common characteristics such as size or location of dehiscence are affecting the absorbance values in this frequency range.

Although the range of frequencies that exhibited a significant difference when comparing absorbance values of SSCD ears to those of the control group were slightly larger when testing at TPP compared to testing at ambient pressure, a marked difference in the results of absorbance at ambient pressure and at TPP were not clearly evident. A 3 way repeated measure ANOVA on the absorbance values

with group, pressure and frequencies as independent factors, and with pressure and frequencies as repeated factors indicated no significant interaction between pressure and group ($p = 0.99$) or pressure/group/frequency ($p = 1.00$). There was therefore no significant interaction between types of pressure and group on absorbance values at different frequency levels. This similarity in absorbance results measured at ambient pressure and TPP could potentially be attributed to the fact that an MEP of between -50 daPa and 50 daPa were included in the selection criteria of participants, with the result that the pressure at which the ambient and TPP tests were administered didn't differ with more than 50 daPa. Further research is required to determine whether a greater difference in absorbance might be observed when testing participants with MEP outside the normative ranges described in literature (BSA, 2013).

The distinctive peak in absorbance around 890.9 Hz that was found in the current study supports the use of WAI testing as a screening test for suspected SSCD. However, a relatively wide normative absorbance range causes the reflectance/ absorbance values around 1000 Hz of SSCD ears to overlap with those of normal ears in some cases (Nakajima et al., 2013). This trend was also observed in the current study. The occurrence of a peak in absorbance around 1000 Hz in ears with a normal audiogram could be the result of a hypermobile TM (Rosowski et al., 2012), while peaks have also been found in ears with ossicular chain discontinuity (OCD) (Farahmand et al., 2016; Karuppannan & Barman, 2020; Nakajima et al., 2012). Furthermore, the peak in absorbance around 890.9 Hz was also not present in every SSCD ear in the current study. Although the peak varied in size, a total of 9 out of the 12 SSCD ears displayed a noticeable peak in absorbance around 890.0 Hz. No obvious pattern of clinical symptoms was reported amongst the three ears that didn't display the peak; therefore other factors such as the size and location of the dehiscence could have had an effect on the presence of a peak, and warrants further investigation. Furthermore, the diagnosis of SSCD ears in the current study had not yet been confirmed surgically, therefore the possibility of false positives cannot be excluded. Therefore it is recommended that WAI results are interpreted in conjunction with clinical symptoms, acoustic reflex results, tuning fork tests (such as the malleolus test), and the audiogram when deciding on further referral for

radiological imaging as well as management once a conclusive diagnosis has been made.

4.1.2 Resonant frequency

The mean RF of the control group in the current study (926 Hz) is similar to the mean RF of the normal group (935.1 Hz) reported by Demir et al. (2019) as well as to the mean RF of normal ears of 964.6 Hz reported by Polat et al. (2015). However, the mean RF of the SSCD group in the study by Demir et al. (2019) of 548.7 Hz (±182.9) was lower than the mean RF of the SSCD group reported in the current study (780.6 Hz ±169.78). Factors such as the size and location of the dehiscence as well as the exclusion of ears with a low frequency component by Demir et al. (2019) might be responsible for this difference. However, the studies were in agreement that a lower mean RF is evident in SSCD compared to normal ears. In general a dehiscence of the sSCC results in increased freedom of stapes motion due to the decrease in the acoustic impedance of the inner ear (Pisano et al., 2012), which could be responsible for a reduction of the stiffness component of the SSCD ear, resulting in a lower RF. A decreased RF compared to those of normal ears, however, is not unique to SSCD. A lower RF was reported in cases of OCD (Karuppannan & Barman, 2020), tympanic membrane perforations (Kim et al., 2019) and enlarged vestibular aqueduct (Sato et al., 2002), while Shanks (1984) listed otitis externa, serous otitis media and tympanic membrane pathology as pathologies that produce a decrease in RF.

For this reason, as well as an overlap of RF values of pathological ears with the RF of healthy ears, the RF in itself cannot be used for diagnostic purposes. However, in cases of unilateral SSCD, a comparison of the RF of the two ears is useful. In the current study, for example, all the participants with unilateral SSCD displayed a lower RF in the SSCD ear than in the non-SSCD ear. Furthermore, the RF as part of a diagnostic test battery could be of potential value in cases where differential diagnosis is required between mass- and stiffness dominated pathologies, especially those that often mimic one another, such as otosclerosis and SSCD.

4.1.3 Admittance magnitude at resonance frequency

Although the AM at 226 Hz of the SSCD ears in the current study was significantly higher than that of the control group (p = 0.038), the mean AM at 226 Hz of the SSCD group (0.94 mmho, ±0.43) was still within the normative range for static admittance at 226 Hz (BSA, 2013). This is in contrast to OCD, where a higher mean AM at 226 Hz in OCD ears of 2.06 mmho (±0.55) was reported by Karuppannan & Barman (2020), who studied the wideband absorbance pattern in adults with otosclerosis and OCD.

Since a probe frequency close to the RF is sensitive to changes both in mass and stiffness, it should be sensitive to all middle ear disease (Shanks, 1984). For this reason the current study reported on the AM as measured at RF, finding the AM at RF of the SSCD group significantly higher (p = 0.010) than that of the control group. However, at this stage no normative data is available for any tympanometric values measured at the RF of the middle ear, and to the knowledge of the authors no previous studies have reported on AM measured at RF for healthy ears, SSCD ears or another pathology. Therefore the results of AM at RF cannot be used for diagnostic purposes in SSCD at present, and further research in this area is recommended to determine its value as part of the test battery.

4.2 Clinical implications

The study illustrated that a peak in wideband absorbance around 890 Hz at TPP and at ambient pressure can be indicative of SSCD. This is in accordance with previous studies performed at ambient pressure (Merchant et al., 2016, 2015; Voss et al., 2012). However, since the peak was not evident in all the participants, it is recommended that the results are utilised as a screening test and interpreted alongside clinical symptoms and other tests such as a CT-scan, VEMP testing and an audiogram. Although the range of frequencies that exhibited a significant difference in the absorbance values of SSCD ears were slightly larger compared to those of the control group, a marked difference in the results of absorbance at ambient pressure and at TPP were not clearly evident. However, in the presence of MEP outside of the normative range of -50 to 50 daPa, measuring WAI at TPP would be desirable.

Adding the measurement of the RF of the middle ear to WAI when testing suspected SSCD ears can be of potential use when differentiating between SSCD and otosclerosis, that often mimic one another by presenting with a low frequency air-bone gap during audiometry (Merchant, Rosowski, & McKenna, 2007). The increased stiffness of the otosclerotic middle ear system often results in an increased RF (Śliwa, Kochanek, Jedrzejczak, Mrugała, & Skarżyński, 2020), while the current study and the study by Demir et al. (2019) suggested a decrease in RF in SSCD ears when compared to the RF of a control group.

While certain middle ear pathologies do not affect AM when measured at 226 Hz, AM measured close to the RF of the middle ear system should be more sensitive to both mass- and stiffness dominated pathologies, since the RF is sensitive to changes both in mass and stiffness (Shanks, 1984). While the researcher is not aware of any published normative data for AM at the RF of the middle ear, the results of the current study suggest that the presence of SSCD results in an increased AM at RF when compared to the AM at RF of a control group. Therefore the results of AM at RF cannot be used for diagnostic purposes in SSCD at present, and further research in this area is recommended to determine its value as part of the test battery.

4.3 Critical evaluation

4.3.1 Strengths of the study

The following were identified as strengths of the study:

- WAI absorbance results at TPP, RF as well as AM at RF of SSCD ears were collected and analysed, presenting a unique set of data. Limited research has been conducted to date that described the absorbance characteristics of SSCD ears at TPP. Furthermore, the researcher is not aware of previously published studies that compared the AM at RF derived from tympanometric data of SSCD ears to those of a control group. The current study illustrated the potential value of including the AM value at RF of SSCD ears when reporting on WAI results;
- Each test was administered three times and the average was used in order to avoid outliers;

- Stringent inclusion criteria were used to identify SSCD participants. Based on recommendations by Ward et al. (2017), CT imaging alone was not accepted as sufficient proof of the presence of SSCD, thereby reducing the possibility of a false positive diagnosis skewing the results.

4.3.2 Limitations of the study

The following were identified as limitations of the study:

- A larger number of SSCD participants in the current study would have been preferable; however, the incidence of SSCD has been reported to be as low as 0.7% of individuals (Carey et al., 2000), therefore time constraints prohibited the researchers to source a larger number of SSCD participants. The low sample size limited the complexity of the statistical analyses, since multivariate tools were not suitable for use in such a small sample. Since this may have introduced a bias, a larger study that would facilitate analysis by multivariate statistical analysis is required to further explore WAI in SSCD.
- Because there were multiple comparisons the risk of a type 1 error (false positive) was higher and therefore further research, focusing on fewer comparisons, is recommended.
- In order to illustrate the benefits of measuring absorbance at TPP as opposed to measuring at ambient pressure, ideally MEP between -50 and 50 daPa should have been excluded from the selection criteria. However, if participants with MEP outside of this range were included, the researcher would have required the assurance that the deviant MEP was not caused by another concomitant middle ear disorder, which would have affected the reliability of the results. Furthermore, a control group with similar deviant MEP would have to be sourced for the purpose of a statistic comparison.

4.4 Recommendations for future research

- Further research on a larger number of participants with SSCD is required to determine whether the decreased high frequency absorbance pattern that was found in the current study is repeated, and whether additional common characteristics such as size or location of the dehiscence are affecting the absorbance values in this frequency range.

- In order to illustrate the benefits of measuring absorbance at TPP as opposed to measuring at ambient pressure, further research could include SSCD participants as well as a control group with MEP outside of the -50 to 50 daPa range, and who do not display any additional middle ear pathology.
- It would be of interest to compare the WAI absorbance characteristics of SSCD ears pre- and post-corrective surgery, to determine whether the correction reduced the peak in absorbance values around 1000 Hz that was measured pre-surgery.
- The value of WAI results in cases where SSCD was surgically confirmed despite negative VEMP results can also be explored. This would serve to determine whether a peak in absorbance around 1000 Hz could be indicative of SSCD even in the absence of an increased oVEMP amplitude.
- Future studies may also attempt to determine whether a correlation exists between the presence of a characteristic peak in absorbance in SSCD ears, and the severity or absence of characteristic SSCD symptoms, the size of the air-bone gap when a low frequency conductive component is present, as well as the size of the dehiscence.
- Lastly, normative data for AM at RF need to be established in order to promote its value in the differential diagnosis of middle ear pathologies.

4.5 Conclusion

This study aimed to describe the absorbance characteristics and tympanometric values of ears with confirmed SSCD measured at TPP and at ambient pressure. Absorbance values measured on SSCD ears showed a peak in absorbance around 890 Hz at both ambient pressure and TPP, similar to findings from earlier studies that found a peak in absorbance/notch in reflectance around 1000 Hz. As a result of the significant difference in RF of SSCD ears compared to those of the control group, the potential value of measuring the RF of the middle ear to differentiate between mass-and stiffness dominated pathologies, was also illustrated. Further research measuring the AM at RF in normal and pathological ears was suggested to determine its clinical value.

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6. LIST OF APPENDICES

Appendix A: Example of permission letter from participating otolaryngologist and audiologists

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019
Department of Speech-Language Pathology & Audiology

June 2019

Dear professional

RE: PERMISSION TO ACCESS PATIENT FILES FOR RESEARCH PURPOSES

I, Hendriena Pieterse, am currently conducting research through the Department of Speech-Language Pathology and Audiology at the University of Pretoria as part of a Master's degree in Audiology. The purpose of the study, entitled "Wideband Acoustic Immittance in Superior Semi-circular Canal Dehiscence", is to examine the middle ear properties of individuals with confirmed Superior Semi-Circular Canal Dehiscence (SSCD) by means of Wideband Acoustic Immittance testing.

For this study, participants are required to have been diagnosed with SSCD. Please refer to Table 1 below for diagnostic criteria recommended by Ward, Carey and Minor (2017).

Table 1: Proposed diagnostic criteria for superior canal dehiscence syndrome (SSCD)[1]

Patients should meet the following conditions:
1. High-resolution computed tomography images (≤0.625-mm slice thickness) reformatted in the plane of the superior SCC demonstrating a dehiscence
2. At least one of the following symptoms consistent with SSCD: A. Bone conduction hyperacusis (in the form of autophony, audible eye movements, audible footsteps, etc.) B. Sound-induced vertigo C. Pressure-induced vertigo (via nasal or glottic Valsalva or pressure applied to the external auditory canal) D. Pulsatile tinnitus
3. At least one of the following diagnostic tests indicating a third mobile window: A. Negative bone conduction thresholds (pseudo conductive hearing loss) on pure tone audiometry B. Enhanced VEMP responses (low cervical VEMP thresholds or high ocular VEMP amplitudes) C. Elevated summating potential to action potential ratio on electrocochleography in the absence of a sensorineural hearing loss
SCC: semicircular canal; VEMP: vestibular-evoked myogenic potential. VEMP thresholds should be compared to laboratory norms.
1. Ward, B.K., Carey, J.P. & Minor, L.B. (2017). Superior Canal Dehiscence Syndrome: Lessons from the First 20 Years. Frontiers in Neurology (8):1-10.

Further requirements are that no ear surgery has been performed and that no other middle ear pathology is present.

Participants will be required to undergo the following tests and actions:

- Interview with the researcher to convey relevant background medical information
- Otoscopy
- 226Hz tympanometry and ipsilateral acoustic reflex testing
- Wideband Tympanometry testing at peak tympanometric pressure
- Wideband Absorbance testing at ambient pressure
- Both ears will be tested; in the instance of unilateral SSCD, the contralateral ear will be used as a measure of control.

The equipment is portable; therefore the testing can be conducted at your rooms, or alternatively at another quiet venue in the vicinity which has been mutually agreed upon by the researcher and the participant.

In order for me to gain informed consent from potential participants that meet the above criteria, I would like to request that a representative of your practice contacts potential participants to request permission that their contact details be made available to me for the purpose of a research study. If they agree I will contact them to ask if they would be willing to participate in the study.

Please note that ethical clearance will be obtained from the Faculty of Humanities of the University of Pretoria.

Participants will be required to give informed consent to participate in the research study and that the contents of their patient files at your practice can be accessed by me. There are no financial obligations related to participation in the research to the participants. There are also no medical risks associated with the research. Participation is strictly voluntary and participants may decide to withdraw their consent at any time without any negative consequences. The information and results gathered will be available in the format of a research dissertation and in a possible journal publication. All participants will have access to all data obtained in this project. The identity of the participants will not be revealed in the research dissertation or any scientific articles and all information is to be treated in the strictest of confidence. Confidentiality will be ensured by assigning an identifying alphanumeric code to each participant that will be used for all data processing. Coded data will be stored for a minimum of 15 years according to University of Pretoria regulations.

You are most welcome to contact me at any stage if you require more information at 083 656 1647 or hendrienap@icloud.com. Alternatively you may contact the supervisors for this study, Dr Leigh Biagio de Jager at email: leigh.biagio@up.ac.za or Prof Bart Vinck, at email: Bart.Vinck@UGent.be.

Kind regards,

Ms Hendriena Pieterse	Dr Leigh Biagio de Jager	Prof Bart Vinck
Audiologist and researcher	**Supervisor**	**Supervisor**

Attention Ms Pieterse and co-researchers

PERMISSION TO ACCESS PATIENT FILES FOR RESEARCH

I hereby grant Ms Pieterse direct access to the patient files of individuals who were previously diagnosed with superior semi-circular canal dehiscence and who consented to participate in the research study entitled "Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence".
The identity of the participants will not be revealed and all information is to be treated in the strictest of confidence.
I also grant Ms Pieterse permission to make use of the questionnaire entitled "Superior Canal Dehiscence (SCD) Questionnaire", as found on www.lmhofmeyr.co.za in the course of her research.

2019/3/19
Date

Dr L. M. Hofmeyr
Otolaryngologist
Mediclinic Muelmed, Pretoria
Netcare Christiaan Barnard Memorial Hospital, Cape Town

DR. L M HOFMEYR
MBChB (Pret) MMED ENT (Pret)
ENT SPECIALIST (Otology & Neurotology)
MP 0408042 / Pr No 030 000 0041637

Attention Ms Pieterse and co-researchers

PERMISSION TO ACCESS PATIENT FILES FOR RESEARCH

I hereby grant Ms Pieterse direct access to the patient files of individuals who were previously diagnosed with superior semi-circular canal dehiscence and who consented to participate in the research study entitled "Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence".
The identity of the participants will not be revealed and all information is to be treated in the strictest of confidence.

Name: M.C. Botha

Signature: MBotha

Attention Ms Pieterse and co-researchers

PERMISSION TO ACCESS PATIENT FILES FOR RESEARCH

I hereby grant Ms Pieterse direct access to the patient files of individuals who were previously diagnosed with superior semi-circular canal dehiscence and who consented to participate in the research study entitled "Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence".
The identity of the participants will not be revealed and all information is to be treated in the strictest of confidence.

Name: Natasha Uijcen

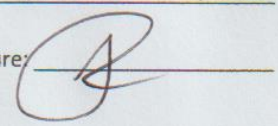
Signature: 

Attention Ms Pieterse and co-researchers

PERMISSION TO ACCESS PATIENT FILES FOR RESEARCH

I hereby grant Ms Pieterse direct access to the patient files of individuals who were previously diagnosed with superior semi-circular canal dehiscence and who consented to participate in the research study entitled "Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence".
The identity of the participants will not be revealed and all information is to be treated in the strictest of confidence.

Name: TARRYN M. REDDY

Signature: 

Appendix B: SSCD group participants letter of informed consent

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019
Department of Speech-Language Pathology & Audiology

January 2019

Dear participant

INVITATION TO PARTICIPATE IN A RESEARCH STUDY

I (Hendriena Pieterse) would like to invite you to participate in a research study entitled: "Wideband Acoustic Immittance in Superior Semi-circular Canal Dehiscence" through the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

1. Information about the research study

The purpose of this study is to examine the middle ear properties of individuals with confirmed Superior Semi-Circular Canal Dehiscence (SSCD) by means of Wideband Acoustic Immittance testing.

2. Participant candidacy

For this study, participants are required to have been diagnosed by an ear-nose-and throat surgeon (ENT) with SSCD by means of a computed tomography (CT) scan. Further requirements are that no ear surgery has been performed and that no or other middle ear pathology is present. If you consent, I will collect all necessary information from your patient file at your treating ENT in order to acquire all information necessary for the study's testing purposes.

3. Requirements from participants

In this study participants will be required to complete the following tests and actions:

	Test Name	Requirements
PROCEDURES	Interview	You will be required to answer a series of questions regarding your general health, hearing, balance, history of ear infections and/or surgery, as well as medication you are currently using.
	Otoscopy	You will need to sit still for the duration of this test while I examine the ear canal and ear drum of both your ears with an otoscope.
	Acoustic immittance and wideband acoustic immittance	You will need to sit still while a probe tip will be inserted into the first section of your ear canal. You will hear a sound and you will feel pressure building up and releasing in the ear canal. You will be requested not to chew or talk during the procedure. This test will be conducted on both ears.

4. Test duration and venue

The entire procedure should not exceed 30 minutes and will be conducted at the referring ENT's rooms or another quiet venue mutually agreed on between the researcher and the participant.

5. Possible risks and benefits of this study

Participants will not be exposed to any risk or experience any discomfort during the testing procedures. There are no direct benefits to participating in this study. However, the data collected in this study will aid in the diagnosis of SSCD.

6. Confidentiality and anonymity

Your personal identifying information will be kept strictly confidential during the reporting of results. If permission is granted by you as the participant, only the researcher, the supervisors and the treating ENT will have access to your information. All information will be treated as confidential and your name will not be used since each participant will be assigned an identifying alphanumeric code which will be used for all data processing. Coded

data will be stored for a minimum of 15 years according to University of Pretoria Regulations.

7. Sharing of results

The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology, but no identifying information will be used at any time. The results of this research may be used by further researchers. If you would like a summary of the findings of this research study, a copy can be made available to you when the project is complete.

8. Refusal or withdrawal from the research

Participation in this research is entirely voluntary; therefore you may withdraw from the study at any point, should you wish to do so.

9. Ethical approval

This study has received written approval from the Research Ethics Committee of the Faculty of Humanities and the Department of Speech- Language Pathology and Audiology at the University of Pretoria.

10. Contact

Should you have any questions or concerns regarding any aspect of this study, please feel free to contact Ms Pieterse at Tel. No: 083 656-1647 or email: hendriena@mymtnmail.co.za. Alternatively you may contact the supervisors for this study, Prof Bart Vinck, at email: Bart.Vinck@UGent.be, or Dr Leigh Biagio de Jager at email: leigh.biagio@up.ac.za.

Kind regards,

Ms Hendriena Pieterse	Dr Leigh Biagio de Jager	Prof Bart Vinck
Audiologist and researcher	**Supervisor**	**Supervisor**

11. Consent to participate in this study

I hereby give consent to participate in the study entitled "Wideband Acoustic Immittance in Superior Semi-circular Canal Dehiscence" undertaken by Hendriena Pieterse. I have also given my consent to the researcher, Hendriena Pieterse, to access my ENT patient file in order for her to acquire all information necessary for the study's testing purposes. I have read and understand the letter explaining the purpose of the research study. I have been given the opportunity to ask the researcher questions about the study and I am satisfied that they have been answered satisfactorily. I am aware that the data in this study may be used in current and future research. I am aware that participation in this study is entirely voluntary and that I may withdraw from this project at any time, and that this will not alter my medical treatment in any way. I am aware that the results of the study, including personal details, will be anonymously processed in research reports. I am participating willingly.
I have received a signed copy of this agreement.

Participant's name: _____
(Please print)

Participant's signature:_____ **Date:** _____

Investigator's name: _____
(Please print)

Investigator's signature:_____**Date:** _____

Witness' name:_____
(Please print)

Witness' signature:_____**Date:** _____

Appendix C: Control group participants letter of informed consent

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019
Department of Speech-Language Pathology & Audiology

January 2019

Dear participant

INVITATION TO PARTICIPATE IN A RESEARCH STUDY

I (Hendriena Pieterse) would like to invite you to participate in a research study entitled: "Wideband Acoustic Immittance in Superior Semi-circular Canal Dehiscence" through the Department of Speech-Language Pathology and Audiology at the University of Pretoria.

1. **Information about the research study**

The purpose of this study is to examine the middle ear properties of individuals with confirmed Superior Semi-Circular Canal Dehiscence (SSCD) by means of Wideband Acoustic Immittance testing.

2. **Participant candidacy**

For this study, participants are required to have been diagnosed by an ear-nose-and throat surgeon (ENT) with SSCD by means of a computed tomography (CT) scan. A control group with no history of SSCD or other middle ear pathology will also be tested for comparative purposes. I would like to invite you to participate in the study as part of the control group. Requirements for the control group are:

- No history of significant middle ear disease (middle ear infection or discharge two or more years previously will not be considered significant if there were no known residual consequences).
- No history of surgery to the ears (ear operations), with the exception of myringotomy or tympanostomy tube placement ("grommets") over two years prior.
- Normal eardrums and no excessive ear wax.
- Hearing within normal limits.
- Normal results on traditional middle ear testing.

The above criteria should be met for both ears of each participant in the control group.

3. Requirements from participants

In this study participants will be required to complete the following tests and actions:

	Test Name	Requirements
PROCEDURES	Interview	You will be required to answer a series of questions regarding your general health, hearing, balance, history of ear infections and/or surgery, as well as medication you are currently using.
	Otoscopy	You will need to sit still for the duration of this test while I examine the ear canal and ear drum of both your ears with an otoscope.
	Hearing test	You will be seated in a sound proof room with headphones on. You will be required to press a button when you hear a tone. The procedure will be repeated with a bone conductor placed behind your ear. The test will be conducted on both ears.
	Acoustic immittance and wideband acoustic immittance	You will need to sit still while a probe tip will be inserted into the first section of your ear canal. You will hear a sound and you will feel pressure building up and releasing in the ear canal. You will be requested not to chew or talk during the procedure. This test will be conducted on both ears.

4. Test duration and venue

The entire procedure should not exceed 45 minutes and will be conducted at a private audiology practice in Kempton Park.

5. Possible risks and benefits of this study

Participants will not be exposed to any risk or experience any discomfort during the testing procedures. There are no direct benefits to participating in this study. However, the data collected in this study will aid in the diagnosis of SSCD.

6. Confidentiality and anonymity

Your personal identifying information will be kept strictly confidential during the reporting of results. If permission is granted by you as the participant, only the researcher and the supervisors will have access to your information. All information will be treated as confidential and your name will not be used since each participant will be assigned an identifying alphanumeric code which will be used for all data processing. Coded data will be stored for a minimum of 15 years according to University of Pretoria regulations.

7. Sharing of results

The results obtained from this research study will be reported in the form of a scientific article and dissertation, which will be available to professionals in the field of audiology, but no identifying information will be used at any time. The results of this research may be used by further researchers. If you would like a summary of the findings of this research study, a copy can be made available to you when the project is complete.

8. Refusal or withdrawal from the research

Participation in this research is entirely voluntary; therefore you may withdraw from the study at any point, should you wish to do so.

9. Ethical approval

This study has received written approval from the Research Ethics Committee of the Faculty of Humanities and the Department of Speech- Language Pathology and Audiology at the University of Pretoria.

10. Contact

Should you have any questions or concerns regarding any aspect of this study, please feel free to contact Ms Pieterse at Tel. No: 083 656-1647 or email: hendriena@mymtnmail.co.za. Alternatively you may contact the supervisors for this study, Prof Bart Vinck, at email: Bart.Vinck@UGent.be, or Dr Leigh Biagio de Jager at email: leigh.biagio@up.ac.za.

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Humanities 100.
1919 - 2019
Department of Speech-Language Pathology & Audiology

Kind regards,

Ms Hendriena Pieterse
Audiologist and researcher

Dr Leigh Biagio de Jager
Supervisor

Prof Bart Vinck
Supervisor

11. Consent to participate in this study

I hereby give consent to participate in the study entitled "Wideband Acoustic Immittance in Superior Semi-circular Canal Dehiscence" undertaken by Hendriena Pieterse. I have read and understand the letter explaining the purpose of the research study. I have been given the opportunity to ask the researcher questions about the study and I am satisfied that they have been answered satisfactorily. I am aware that the data in this study may be used in current and future research. I am aware that participation in this study is entirely voluntary and that I may withdraw from this project at any time. I am aware that the results of the study, including personal details, will be anonymously processed in research reports. I am participating willingly.
I have received a signed copy of this agreement.

Participant's name: _____
(Please print)

Participant's signature:_____ **Date:** _____

Investigator's name: _____
(Please print)

Investigator's signature:_____**Date:** _____

Witness' name:_____
(Please print)

Witness' signature:_____**Date:** _____

Appendix D: Case history and results

CASE HISTORY AND RESULTS

Participant Alphanumeric Code: _____ Date:_____

CASE HISTORY:

Do you have difficulty hearing?			**YES**	**NO**
Which is your better hearing ear?	**SAME**		**RIGHT**	**LEFT**
Have you received any medical or surgical treatment for hearing loss or middle ear pathology? If yes, please elaborate:			**YES**	**NO**
Any drainage from the ear in the past two years?			**YES**	**NO**
Have you had pain/discomfort in your ears in the past two years?			**YES**	**NO**
Do you have any noises or ringing in your ears?			**YES**	**NO**
If yes, which ear?	**BOTH**		**RIGHT**	**LEFT**
When did it start?				
Have you ever been exposed to loud noise?			**YES**	**NO**
If yes, please elaborate:				
Is there a history of hearing loss in your immediate family?			**YES**	**NO**

Have you been diagnosed with or suffer from any of the following conditions?

Diabetes		Heart problems		Head injury	
High blood pressure		Headache/ migraine		Malaria	
Cancer		Meningitis/encephalitis		High cholesterol	

Other:
Please provide a list of medication you are currently using:
Any surgery or complications during surgery:
General comments:

Adapted from the IDA institute audiology case history form, retrieved from:
https://idainstitute.com/fileadmin/user_upload/Downloads/Case%20History%20Form.docx

RESULTS:

Participant Alphanumeric Code: _____ Date:_____

Research group ☐

Control group ☐

SSCD ear (research group):

Left ☐

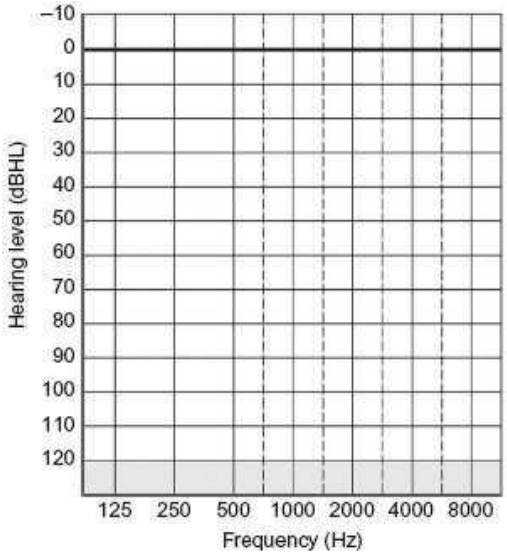
Right ☐

Bilateral ☐

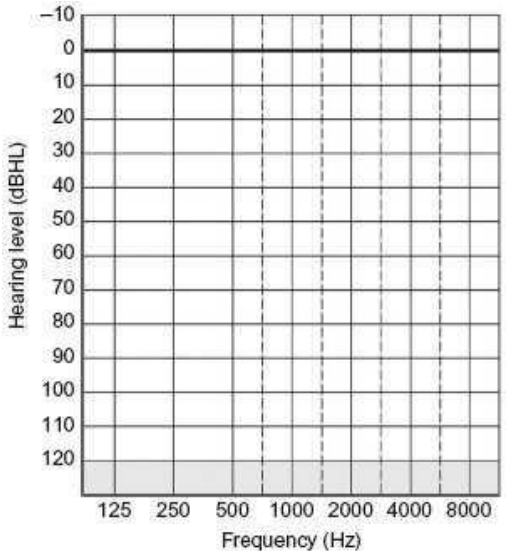
Otoscopic evaluation:	
Right ear:	
Left ear:	

Audiogram (control group only):

Right ear:



Left ear:

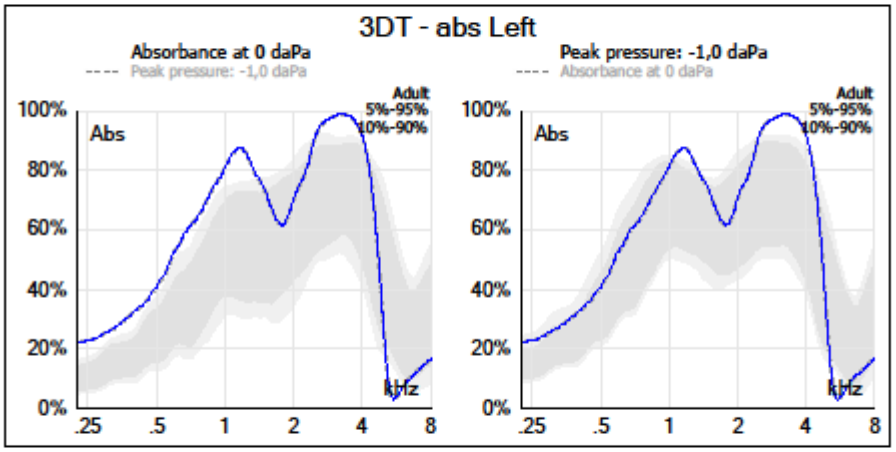


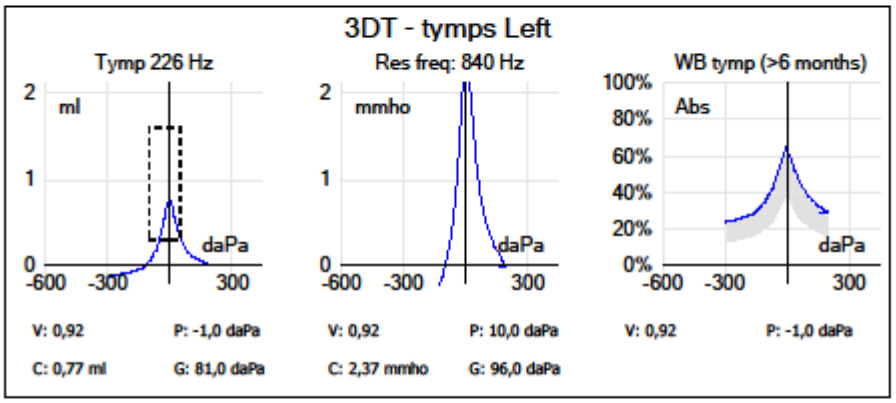
Example of WAI results (printed directly from Titan software):

Participant:

First name Test2RG
Last name Test2RG

Session Date: IMP 2019/06/29 4:27:41 PM





Appendix E: SSCD questionnaire

dr. louis hofmeyr

SUPERIOR CANAL DEHISCENCE(SCD) QUESTIONNAIRE

Name_____ Date_____

Instructions

1. Complete this questionnaire by marking the applicable block.
2. Scale your symptoms from 1 to 5 where:
   a. 1 means you are not bothered at all by the symptoms.
   b. 5 means you are completely disabled by the symptoms.
3. The following scale is not verified but can help to monitor the response on treatment.

	Symptom	1	2	3	4	5
1	Hearing your own voice in the affected ear					
2	Hearing your own footsteps, eye movements or breathing in the affected ear					
3	Hearing your own heartbeat in the affected ear					
4	Loud sounds causes dizziness					
5	Straining or lifting heavy objects causes dizziness					
6	Nose blowing or equelizing the ears causes dizziness					
7	Hearing loss in the affected ear					
8	Pressure and fullness in the affected ear					
9	General disequilibrium/ imbalance					

Adapted from

Silverstein H, Kartush JM, Parnes LS, Poe DS, Babu SC, Levenson MC, Wazen J and Ridley RW. Round window reinforcement for superior semicircular canal dehiscence: A retrospective multi-center case series. *AMERICAN JOURNAL OF OTOLARYNGOLOGY–HEAD AND NECK MEDICINE AND SURGERY*.2014;35:286–293.

Dr. LM Hofmeyr
OTOLOGIST AND NEUROTOLOGIST
MBChB(UP) MMED ENT (UP)
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Pr. No. 0041637
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Reg. no. inc 2013 / 017579 / 21
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C 082 339 4926

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Appendix F: Ethical clearance form: Faculty of Humanities

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
YUNIBESITHI YA PRETORIA

Humanities 100.
1919 - 2019
Research Ethics Committee

9 April 2019

Dear Miss H Pieterse

Project Title:	Wideband Acoustic Immittance in Superior Semicircular Canal Dehiscence
Researcher:	Miss H Pieterse
Supervisor:	Dr L Biagio de Jager
Department:	Speech Language Path and Aud
Reference number:	HUM025/0319
Degree:	Masters

I have pleasure in informing you that the above application was **approved** by the Research Ethics Committee on 4 April 2019. 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.

We wish you success with the project.

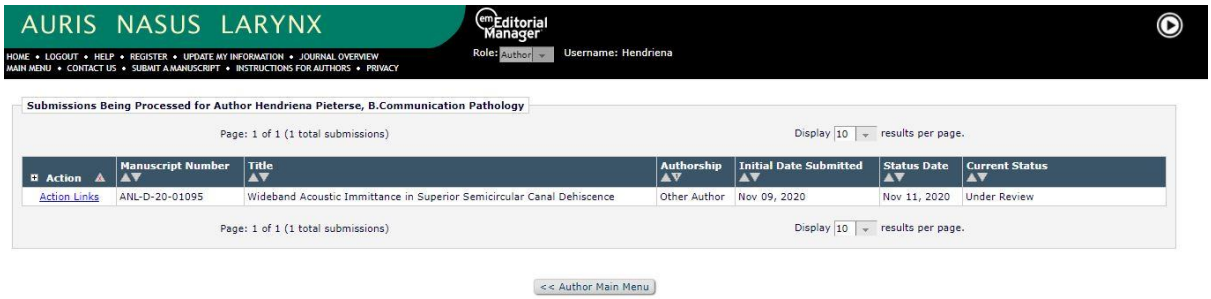
Sincerely

Prof Maxi Schoeman
Deputy Dean: Postgraduate and Research Ethics
Faculty of Humanities
UNIVERSITY OF PRETORIA
e-mail: PGHumanities@up.ac.za

Fakulteit Geesteswetenskappe
Lefapha la Bomotho

Research Ethics Committee Members: Prof MME Schoeman (Deputy Dean); Prof KL Harris; Mr A Bizos; Dr L Blokland; Dr K Booyens; Dr A-M de Beer; Ms A dos Santos; Dr R Fasselt; Ms KT Govinder Andrew; Dr E Johnson; Dr W Kelleher; Mr A Mohamed; Dr C Puttergill; Dr D Reyburn; Dr M Soer; Prof E Taljard; Prof V Thebe; Ms B Tsebe; Ms D Mokalapa

Appendix G: Proof of submission of article



Appendix H: Declaration of originality

UNIVERSITY OF PRETORIA

DECLARATION OF ORIGINALITY

This document must be signed and submitted with every essay, report, project, assignment, dissertation and / or thesis.

Full names of student: HENDRIENA PIETERSE .....

Student number: 96062012.....

Declaration

1. I understand what plagiarism is and am aware of the University's policy in this regard.

2. I declare that this dissertation is my own original work. Where other people's work has been used (either from a printed source, Internet or any other source), this has been properly acknowledged and referenced in accordance with departmental requirements.

3. I have not used work previously produced by another student or any other person to hand in as my own.

4. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as his or her own work.

SIGNATURE OF STUDENT: