Clinical applications

The middle ear is a complex mechanism with many components. There are many possible disorders of the middle ear, including fluid in the ear, ossification of the bony structures,
discontinuities of the ossicular chain, and perforation of the eardrum, as well as abnormalities of the membranes, ligaments, and supporting structures. Since the middle ear is involved in virtually every test of hearing, it is critical to ascertain the middle-ear status at the outset of any audiological evaluation, and, in the case of abnormal middle-ear function, pinpoint the cause to enable an appropriate intervention. Wideband reflectance measurements evaluate the middle ear over a wide frequency range (0.2 to 6 kHz, or higher), allowing clinicians to make more nuanced interpretations of hearing health. For no extra effort, the forward pressure level can be used to improve stimulus calibration, and increase test validity and reliability.

WAI is a new non-invasive clinical test method for ME evaluation. There are many approaches to establish diagnostic criteria. Statistical methods are used to establish the normal range, and to identify criteria for what is abnormal. Scientific models are used to simulate and understand the underlining principles of the mechanism in normal and abnormal conditions. Combining the outcome of these methods allows us to derive workable diagnostic criteria. In the discussions below, different studies demonstrate different approaches to establish criteria. In this section, except where indicated, the described findings can be used by clinicians and researchers with clinical WAI equipment. In some cases the diagnostic criteria are built in, and in other cases, the clinician or researcher may need to derive the result from the exported data. The clinical utility of WAI is undergoing intensive research, and the outcomes are rapidly advancing into clinical applications.

Quantities used

A single WAI measurement produces a wealth of information. High-resolution analysis provides frequency resolution in the order of 20 Hz over at least a 0.2 to 6 kHz range. Multiple quantities may be derived, as described earlier, from power reflectance and absorbance to a range of other immittance values. Typically, this is too much information to
work with statistically for the purpose of clinical decision making (e.g., looking for a significant difference across 248 individual frequency points is bound to produce multiple false positive and false negative errors). Thus, clinical researchers have developed various tactics to reduce the number of variables and extract meaningful quantities to assist diagnostic decision making. Current approaches include:

1. *Looking for patterns.* Small-N and case studies are used to get an idea of the general pattern of normal and abnormal results, particularly when characterizing relatively unstudied pathologies. This can help focus attention onto specific frequency ranges in larger studies, and improve detection based on physical modeling.

2. *Band averaging.* Band-averaging reflectance and absorbance level across frequency can describe frequency-dependent behavior of WAI using a smaller set of parameters (Hunter, Feeney, Lapsley Miller, Jeng, & Bohning, 2010). One-third, one-half, and whole octave bands are frequently used, and fit nicely with other audiological tests, while still capturing the shape of the reflectance curve. It is not typically useful to take the average across the entire curve, because frequency dependent behavior will be obscured.

3. *Comparison to norms.* Comparing abnormal results to a norm can be done qualitatively and quantitatively. For instance, the Absorbance Level Difference (ALD), defined by Rosowski et al. (2012), is the absorbance level relative to a normal ear average over a specific frequency range. They used the ALD to quantify notches seen in abnormal absorbance curves.

4. *Parameterization.* Involves modeling the reflectance or absorbance curve with a small number of parameters, such as a three-line approximation to the absorbance level curve (Rosowski et al., 2012).
5. **Multivariate Approaches.** Methods such as discriminant function analysis and multiple regression can help the researcher narrow down variables that provide the most unique information. These approaches can also allow information to be combined across test types and across measurements with different units, providing a powerful basis for clinical decision making. Multiple parameters are combined to produce one number, which is then used for making a decision.

6. **Reflectance Phase Analysis.** Of particular interest is separating the complex (magnitude and phase) pressure reflectance into ear canal and tympanic membrane components, as this retains time-delay information at the tympanic membrane. A number of investigators have proposed methods to remove ear canal phase effects.

**Norms**

For clinical use, what first needs to be established is the normal range of immittance quantities, broken down by key demographics such as sex, ear, age, and ethnicity. With information about how normal ears behave, ears with middle-ear dysfunction may be identified. A norm is a statistically defined range for a given quantity, derived from a group of highly-screened normal ears for a specific demographic group. The type and degree of screening for defining “normal” varies across studies, but includes audiological history and audiological tests such as AABR, OAE, tympanometry, surgical discovery, and pneumatic otoscopy. Different screening tests and criteria can be a reason for differences between norms across studies. Norms can be expressed in various ways, including percentile ranges and means with standard deviations. Taking a norm may obscure individual patterns across frequency, which is why we have overlaid the norms in Figure XYZ with some case examples.
For WAI, the demographic that has the greatest effect on the middle ear is age, followed to a much lesser extent by ethnicity. Sex and ear differences are much smaller, and typically not observed. Here we focus on the age demographic and describe some key normative studies, with additional discussion about secondary demographic differences. Across many studies, the general consensus is that more larger-N normative studies are needed with highly-screened normal ears. Many existing norms are based on small N, especially by the time they are divided into various demographic groupings. Notable gaps include older children and teenagers, and the elderly. There has been a focus on infants and young children due to their high prevalence of middle-ear disorders.

[Add figure using norms from OtoStat 2.0 for newborns, infants, children, and adults, plotted as reflectance and absorbance – Judi to do.]

**Newborn and infant norms:** The human ear undergoes significant maturation in the first 12 months of life (as summarized in Kei, Sanford, Prieve, & Hunter, 2013). They found that the largest changes in WAI norms occur between birth and 6 months of age, indicating that this is the period of most rapid change in the outer and middle ear. Aithal, Kei, and Driscoll (2014b) showed that developmental changes in the outer and middle ear over the first 6 months of life cause a decrease in absorbance for low- to mid- frequencies, and an increase in absorbance at higher frequencies (>2.5 kHz). The absorbance at low frequencies is dominated by compliance characteristics of the ear canal and middle ear; with maturation, ossification of the inner two-thirds of the ear canal causes the ear canal to be less compliant, and thus less absorptive (Kei et al., 2013). With age, changes in ossicle bone density, along with the loss of mesenchyme and other middle ear fluids, leads to decreased mass in the middle ear system (Aithal et al., 2014b; Kei et al., 2013). This leads to an increase in the ME absorbance at high
frequencies, as the lower mass causes less of the signal to be reflected. This rapid maturation means norms are potentially needed for many age bands.

Norms from newborn babies in the first hours to first days of life are of particular interest due to large-scale newborn hearing screening programs that test babies soon after birth. In Absorbance, the norms typically show unreliable results below 1 kHz due to environmental noise and ear-tip leaks, high absorbance at 1-2 kHz (higher than in older ears), decreasing at 3-4 kHz, and rising again at 6 kHz (which is also not seen in norms for older ears). Figure 1 shows norms from the Hunter et al. (2010) study, recalculated to show the entire frequency range and to show absorbance. Similar norms were also shown by others (Aithal et al., 2013; Sanford et al., 2009; Shahnaz, 2008), with differences mainly due to screening criteria for “normal”, demographics, and equipment. For instance, the ear canal contribution to WAI varies across measurement systems and testers, as some types of probes are inserted more deeply into the ear canal than others.

Aithal et al. (2013) correctly pointed out that using just DPOAE pass/refer results (as the earlier studies did) was not sufficient as a gold standard for normal ears, because ears with strong DPOAEs can overcome middle-ear dysfunction; however, they found similar norms with a smaller, more highly-screened group. For newborns, there is ambiguity in defining the “normal” condition, because it is natural for healthy newborns to have some fluid in their external and middle ears, which affects ME measurements. Whether this is an issue or not depends on the purpose. If the aim is to understand the normal infant ME, it is important. But if the purpose of is to assess infant inner-ear status (as in UNHS programs) any temporary ME condition that affects sound propagation is of concern regardless of whether it is “normal” or not.
Sex and ear differences are typically not observed or are not clinically significant; however, difference in ethnicity were found by Aithal, Kei, and Driscoll (2014a) where Australian Aboriginal infants had lower wideband absorbance than Australian Caucasian infants. This could be of clinical importance due to the high otitis media with effusion (OME) prevalence among Aboriginal children.

For slightly older infants, Hunter, Tubaugh, Jackson, and Propes (2008) produced norms for infants 3 days to 47 months old. They did not find significant age or sex effects, although their age bands had only around 10 ears per band.

The study with the largest number of normative subjects for young children is Beers, Shahnaz, Westerberg, and Kozak (2010). They tested wideband reflectance in 78 children.
(144 ears) age 5-7 with normal middle-ear function for comparison to those with OME. Of interest is the comparison between Caucasian and Chinese children’s ears, where significant differences were found at 2 and 6 kHz. As we’ll see, 2 kHz is an important frequency for detecting conditions that increase middle-ear stiffness, like OME, so this may be of clinical significance. It remains to be studied if body size is a better predictor of variation in reflectance than ethnicity.

**Adults:** Rosowski et al. (2012) established norms on a medium-sized group of highly screened otologically-normal adults (29 adults/58 ears, up to age 64). They found small sex and ear differences, and their overall average reflectance curve was similar to previous studies. Of interest is the parameterization of the absorbance curve. In log-log coordinates, the curve can be modeled with 3 straight lines (Allen, Jeng, & Levitt, 2005; Rosowski et al., 2012). Below 1 kHz, absorbance increases by about 15 dB per decade. Above 4 kHz, absorbance decreases by 23 dB per decade. Between 1 and 4 kHz, absorbance is essentially constant at around -2.5 dB. Extracting the key features of the absorbance/reflectance curves and deriving parametric values to characterize them could aid in clinical decision making. For instance, changes in slopes or frequency of intercepts, or deviation from a straight line may be indicative of abnormal ME performance.
Summary: As discussed by Shahnaz, Feeney, and Schairer (2013) norms age, gender,

Middle-ear dysfunction

A number of small-N and case studies have suggested where WAI might be useful for detecting ME abnormalities, and they provide a descriptive patterns of the conditions relative to norms (e.g., Allen et al., 2005; Feeney, Grant, & Marryott, 2003; Sanford & Brockett, 2014). These studies suggest where larger studies should look. However, we need larger N studies to understand how reflectance behaves statistically in the population, for each pathology and demographic. These results must then be combined and reduced to specific criteria for decision making. Needed are larger N studies for specific pathologies, as well as across a range of confusable pathologies to reveal differential diagnoses. Fortunately, a number of such studies are occurring, and we will summarize some here.

As discussed by Voss (2012), although the clinical data shows systematic differences in the presence of pathology due to physiological changes, the high degree of variability across normal subjects can mean that it is not always possible to clearly differentiate normal from diseased ears. In most cases, no test on its own will provide a definitive diagnosis. However, the addition of WAI to the audiologist’s arsenal provides new information that improves on our current abilities to detect and diagnose pathology.
WAI in universal newborn hearing screening programs

The goal of universal newborn hearing screening (UNHS) programs is to detect babies who have sensorineural hearing loss so they can benefit from early intervention (e.g., cochlear implants). UNHS programs provide a Pass or Refer result from either OAE or ABR tests. These screening tests are not diagnostic, but are used to determine referrals for more extensive diagnostic follow-ups.

It has long been best-practice in UNHS programs to rescreen babies who get a Refer result to reduce false-positives for diagnostic referrals. This rescreening is usually done after a delay, because testing within 24 hours of birth is much more likely to produce a refer result than testing after 24 hours (and preferably 36 hours). The majority of these false-positive referrals are from transient middle-ear dysfunction from the birth process (e.g., amniotic fluid, mesenchyme, and meconium in the middle-ear space), which clears within the first few days of life. Hunter et al. (2010) showed why rescreening OAEs after a delay was often successful – middle-ear reflectance tends to decrease over time, presumably as the middle ear clears, allowing more sound to propagate into the inner ear and back.

This transient middle-ear dysfunction is not reliably picked up with tympanometry in newborns. Hunter et al. (2010) and Sanford et al. (2009) both showed that WAI reflectance was vastly superior to tympanometry in predicting which ears would show low OAE levels due to middle-ear dysfunction. Adding WAI to OAE screening can potentially identify those babies most in need of diagnostic follow-up, help determine the best time for repeat screening, and reduce false-alarm referrals.

WAI can be used to interpret OAE results in older infants, children, and adults similarly to newborns. In these older age-groups; however, high reflectance/low absorbance is also cause for follow-up for middle-ear dysfunction like otitis media.
Call out box – WAI in UNHS

When using WAI with OAEs in testing newborns, a pass/refer result can be assigned to each test, giving four possible outcomes. Each outcome is illustrated in Figure 2 with real examples from real babies in the Hunter et al. (2010) study. This study showed that the reflectance/absorbance around 2 kHz was the best predictor for whether the DPOAE test passed (DPOAE levels at 3 or 4 out of 4 frequencies are normal) or not (DPOAEs at 2 or more out of 4 frequencies are abnormally low). So although absorbance is plotted from 1 to 6 kHz, pay particular attention to the 2 kHz region. Reflectance below 1 kHz is not plotted because in babies this region is often noisy and therefore is less diagnostic (Hunter et al., 2010).

Also plotted are two normative regions in gray. For the absorbance plot, the gray norm represents an ambiguous region. Absorbance above this region (especially at 2 kHz), was associated with DPOAE pass results. Absorbance below this region (especially at 2 kHz) was associated with DPOAE refer results. The ambiguous region is defined where the Pass and Refer regions overlap (defined by the 10th and 90th percentiles). Similarly, for the DPOAE plot, the gray norm also represents an ambiguous region (from the Boystown norms (Gorga et al., 1997)). DPOAEs above this region are associated with normal hearing. DPOAEs below this region are associated with abnormal hearing.
Figure 2. Four outcomes are possible when using wideband absorbance at 2 kHz with DPOAEs in a newborn hearing screening program. The absorbance plots show power absorbance (black line, dB re 100% absorbed) and the normative ambiguous region (gray region, dB re 100% absorbed). The DPOAE plots show DPOAE amplitude (white bar, dB SPL), the noise floor (black bar, dB SPL), and the Boystown 90% ambiguous region (gray region, dB SPL), where DPOAEs below the region are considered refer results. For the screening protocol used in this study, if 3 or 4
out of 4 DPOAE frequencies get a pass result, the overall result is a pass (left plots). If 2 or more out of 4 DPOAE
frequencies get a refer result or are noisy, the overall result is a DPOAE refer (right plots). Referrals can be reduced
by considering absorbance. If absorbance is low, the DPOAE refer is probably due to middle-ear dysfunction (top
right). However, the possibility of underlying sensorineural hearing loss cannot be excluded, so repeat screening is
needed. If absorbance is normal, the DPOAE refer needs diagnostic follow-up for possible sensorineural hearing loss
(bottom right). Sometimes absorbance will be low but the DPOAEs are so strong, they are able to overcome the
reduction in middle-ear transmission (bottom left).

How could WAI be used in UNHS programs? Specific guidelines are still in
development, but potentially WAI can be used to enable smarter timing for rescreenings and
follow-ups. For instance, in the examples in Figure 2, the following courses of action may be appropriate:

1. Normal absorbance – normal DPOAEs across all frequencies (top left). Screening
passed and no rescreening or follow-up is needed.

2. Low absorbance – low DPOAEs: possible middle-ear fluid (top right). Wait a few
hours and rescreen to see if absorbance is higher and DPOAEs pass. Refer for
diagnostic follow-up if DPOAEs do not pass on rescreening. Chances are absorbance
will increase as the middle ear clears and the true DPOAE status will be more clearly
revealed. Low absorbance and low DPOAEs is commonly seen in newborn hearing
screening programs, and causes undue worry for parents and an increased workload
due to unnecessary diagnostic follow-ups. With WAI + DPOAEs, testers can
immediately see if there is middle-ear dysfunction and can reassure parents that this is
common and not of concern.

3. Normal absorbance – low DPOAEs (bottom right). This ear is a priority for diagnostic
follow-up because it may be permanent sensorineural hearing loss. Rescreening is
optional because the usual reason for DPOAE false-alarms – low middle-ear
absorbance from transient middle-ear dysfunction – has been eliminated. Any
rescreening can occur immediately because the WAI results show the middle ear is not impeding sound propagation into the inner ear.

4. Low absorbance – normal DPOAEs (bottom left). The DPOAEs are strong enough to overcome what is possibly a probe blockage or transient middle-ear dysfunction. In this situation, the tester should check for probe or ear canal blockage, or a collapsed ear canal, and then retest WAI. Since DPOAEs passed, rescreening is optional because an outer or middle-ear condition is not typically a reason for referral.

**Identifying OME/CHL in infants and children**

Identifying conductive hearing loss (CHL) in young infants can be difficult to do with tympanometry, and there is no standard interpretation. Prieve, Vander Werff, Preston, and Georgantas (2013) evaluated tympanometry variations along with wideband reflectance, and showed the latter was just as effective as tympanometry in identifying CHL in infants less than 6 months old (3-26 weeks) who had been referred in an infant hearing screening program. The babies received both air and bone ABR tests along with tympanometry and wideband reflectance (43 ears had normal hearing and 17 ears had CHL, determined from the air- and bone-conducted ABR thresholds). Prieve et al. found that wideband reflectance between 800 and 3000 Hz was higher in CHL ears compared with normal ears. This is consistent with increased stiffness in the middle ear. Prieve et al. found that a criterion for reflectance greater than 69% in the one-third octave band around 1600 Hz produced the highest likelihood ratio for CHL, compared to other reflectance bands and compared to various quantities derived from multi-frequency tympanometry (at 226, 678, and 1000 Hz). These results indicate the frequency range most sensitive to CHL in infants, and that WAI is a suitable replacement for tympanometry in this age group. But with only 17 ears with CHL, a larger study is needed to more accurately determine appropriate criteria, as well as
investigating if age-specific criteria are needed due to rapidly changing middle-ear physiology in the first year of life.

In children, otitis media is the most common reason for CHL. Middle-ear effusion (MEE) and negative middle-ear pressure (NMEP) tends to stiffen the middle ear and thereby increase the amount of energy reflected, particularly around 1-3 kHz, compared to normal ears. This increased reflectance can be used to identify MEE. Hunter et al. (2008) points out that tympanometry is unreliable in very young infants, and that it can produce normal results in the presence of MEE. It is important to be able to diagnose MEE in this population. They evaluated wideband reflectance for its ability to detect MEE and found particularly between 1-3 kHz that reflectance was higher in ears with suspected MEE compared to normal ears.

Beers et al. (2010) tested 78 children (144 ears) with normal middle ears and 64 children with abnormal middle ears (21 ears with suspected MEE, 21 ears with confirmed MEE, and 54 ears with negative middle-ear pressure). The children were aged 5-7 years. They found that reflectance in the frequency region around 1.25 kHz best separated the normal ears from those with MEE. Using the 90th percentile from the normal group as a criterion, all ears with MEE had higher reflectance than the criterion at 1.25 kHz (hit rate 100%), for a false-alarm rate of 10%. They also showed that reflectance was much more sensitive than 226 Hz tympanometry in detecting MEE. On average, ears with negative middle-ear pressure had higher reflectance than normal, but not as high as those ears with MEE.

Ellison et al. (2012) also investigated MEE in children, and found similar results to Beers, with decreased absorbance between 1.5 and 3 kHz in ears with surgically verified MEE. They also looked at admittance magnitude and phase. ROC analysis indicated that a slight improvement might be found by combining measures, but the key discriminative information
is found in the absorbance function and there is little more to be found in the other measures because they are not statistically independent.

Summary (Nakajima, Rosowski, Shahnaz, & Voss, 2013) (Prieve, Feeney, Stenfelt, & Shahnaz, 2013) reviewed 8 studies that investigated WAI as a method to predict CHL (defined by ABG).

**Ossicular chain pathology in adults**

Ossicular discontinuity can present with a notch in the reflectance curve below 1 kHz. Stapes fixation/otosclerosis tends to produce higher than average reflectance at lower frequencies, but may be within normal limits, or even lower than normal.

The disruption or near-disruption in an ossicle joint creates an extreme resonance, which appears as a notch in the reflectance, or a peak in the absorbance. Although the absorbance is elevated, this power is *not* transmitted to the inner ear, but is dissipated in the resonant joint. We see this in some other pathologies, such as eardrum perforation, where power is dissipated in the ME cavity at the resonant frequency, not transmitted to the inner ear (like when you blow over the opening of a bottle and it sounds a tone.)

Shahnaz et al. (2009) found increased reflectance below 1 kHz in otosclerotic ears, compared to a normal group. This is due to increased stiffness of the ME at the stapes, which
increases the total stiffness of the ME measured at the eardrum. They found that reflectance was a better predictor than tympanometry, with an 82% hit rate and 17% false alarm rate. 500 Hz was identified as a good band for detecting otosclerotic ears. They also identified a subgroup of ears where reflectance was lower than normal below 1 kHz. The combination of reflectance and tympanometry was able to detect all otosclerotic ears for the price of a higher false-alarm rate. Now although these finding show the ability to detect otosclerotic ears, Shahnaz et al used a group of ears with known otosclerosis. Of interest is whether otosclerosis can be differentiated from other middle-ear disorders, which is the situation clinicians’ face.

**Semicircular canal dehiscence (SCD)**

Ears with SCD tend to show a notched reflectance curve around 1 kHz, compared to normal ears (Nakajima et al., 2012), and which is higher in frequency than typically seen with ossicular discontinuity, and smaller and wider. [Sarah – I haven’t found a description for the phys/phys reason why. I’m sure I’ve seen it but can’t find it.]

**Tympanic membrane perforations or PE tubes**

![Reflectance graph](image)

*Figure 3. Four examples of TM perforation in adult ears, compared to the Rosowski norms.*

Tympanic membrane perforations or pressure-equalization tubes tend to produce reflectance curves that are highly variable across frequency, with low reflectance at low
frequencies. In addition, the equivalent ear canal volume is typically \( \gg 3 \text{cc} \). It can be difficult to differentiate a noisy test with an acoustic leak from a TM perforation; however, repeated testing should reveal a stable pattern for a perforation.

As in the case of ossicular discontinuity, although the absorbance is elevated due to TM perforation, this power is \textit{not} transmitted to the inner ear, but is dissipated in the ME cavity.

Larger perforations are detectable with otoscopy, but smaller perforations may be hard to visualize. Curiously, in a cadaveric ear, smaller perforations were more easily seen with WAI than larger ones (Nakajima et al., 2013; Voss, Merchant, & Horton, 2012), presenting as very low reflectance around 1 kHz.

\textit{Negative middle-ear pressure and Eustachian tube dysfunction}

NMEP can occur from ETD and otitis media and its presence stiffens the middle ear. Large degrees of ME pressure distinctly show in the reflectance curve as increased, flat reflectance, especially below 2 kHz. ME pressure cannot be directly estimated from WAI as is the case with tympanometry (i.e., from tympanic peak pressure readings). The degree of MEP is associated with degree of reflectance, but this is only noticeable when considering changes in a subject or perhaps in group averages – it is not easy to detect degree of NMEP from single measurements unless it is severe. It is important to evaluate presence of NMEP as it can affect other measurements, especially OAEs (even with “clinically normal” amounts of NMEP).[Sarah – we’ve both done work on NMEP but mine is published only as a poster so far. Perhaps it’s better we use Sue’s data here?]

\textit{Differential diagnosis of CHL in adults}

It should now be apparent that although some pathologies are easy to detect from normal, they can be quite hard to tell apart from one another because their measurable effects are similar, despite having different causes. For instance, otosclerosis and negative middle-ear
pressure can both cause an increased stiffness as seen at the eardrum even though that
stiffness is generated in different ways. WAI on its own is not able to differentially diagnose
all ME disorders, however in conjunction with other tests (such as ABG), different disorders
can be teased out, including some conditions where it had been previously difficult,
expensive, or not possible.

CHL with an intact TM and aerated middle-ear can be associated with three conditions:
ossicular fixation (usually from otosclerosis), ossicular discontinuity, and superior
semicircular canal dehiscence (SCD), (Nakajima et al., 2012). They are challenging to
differentially diagnose in the clinic, and may require surgery or expensive tests to fully
investigate. Nakajima et al. (2012) showed how to use WAI and an air-bone gap (ABG)
audiogram to aid in the differential diagnosis in an office setting.

The absorbance level difference (ALD) used by Nakajima et al. (2012), is calculated by
subtracting the absorbance (in decibels) from the mean normative absorbance value of -3.42
dB, derived in the companion paper by Rosowski et al. (2012), which considered normal
rather than pathological ears. The ALD averaged over 0.6-1 kHz is the key WAI statistic. The
ABG they use for the differential diagnosis is defined as the average gap between 1 and 4
kHz (this separates out the SCD cases where the ABG is most apparent at frequencies less
than 1 kHz). This test is applicable to patients presenting with CHL, defined as >10 dB air-
bone gap (ABG) on pure-tone audiometry (averaged over either 500, 1000, 2000 Hz or 250,
500, 1000 Hz), and with an intact TM and aerated middle ear.

Nakajima et al. (2012) found:

- Ears with ALD (0.6-1kHz) < 1 dB and ABG (1-4kHz) > 10 dB were associated
  with stapes fixation.
• Ears with ABG (1-4kHz) \( \leq 10 \text{ dB} \) were associated with SCD.

• Ears with ADL (0.6-1kHz) \( \geq 1 \text{ dB} \) and ABG (1-4kHz) > 20 dB were associated with ossicular discontinuity.

In this study, sensitivity and specificity were good (stapes fixation: 86%/100%, ossicular discontinuity: 83%/96%, and SCD: 100%/95% for sensitivity and specificity respectively), but they are based on a small number of subjects (N=31 ears). These results suggest a larger study is warranted to further refine the differential diagnostic potential of WAI and audiometry.

**Sarah’s work**

**Wideband Tympanometry**

Our focus here has been on WAI made at ambient pressure. A variation involves pressurizing the ear canal as in tympanometry, the result being reflectance as a function of frequency and pressure, typically represented as a three dimensional magnitude plot. Advantages to this technique include the ability to slice the results by frequency or by pressure. Disadvantages include a much more complicated set of information to parse into clinical decision making framework, the need to pressurize the ear canal, and the effects pressurization can have on subsequent measurements (preconditioning) (Burdiek & Sun, 2014). Clinical efficacy is still being established; for example, Keefe, Sanford, Ellison, Fitzpatrick, and Gorga (2012) did not find an advantage to adding pressurization in detecting CHL in children.

**What the future holds…**

Clinical advantages

Rich field for theoretical and clinical research
References


