Normative reflectance and transmittance measurements on healthy newborn and one-month old infants

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Abstract

Objective: Ear-canal-based wide-band reflectance (WBR) measurements may provide objective measures to assess and monitor middle-ear status in young babies. This work presents the WBR measurements of power reflectance and transmittance on populations of healthy newborn babies (3-5 days) and healthy one-month old babies (28-34 days). Thus, this work determines how power reflectance and transmittance vary between newborn and one-month old babies and characterizes the range of these measures in normal populations.

Design: Power reflectance and transmittance were calculated from pressure measurements made in the ear canals of eight newborn (15 ears) and eleven one-month old (19 ears) babies. Permutation tests were used to compute p values that tested the effects of age (newborn vs. one month), gender, and ear side (right versus left).

Results: At most frequencies, power reflectance and transmittance did not differ between the two groups tested. For the age comparison, the results suggest a possible difference between newborn and one-month old ears near 2000 Hz. There are essentially no differences between the male and female ears, with the exception of a possible difference in a narrow frequency band near 6000 Hz for the newborn ears. There are possible differences between newborn left and right ears in two narrow frequency bands: near 1200 Hz and near 3000 Hz, and there are no signs of left versus right difference in the one-month-old babies.

Conclusions: At most frequencies, power reflectance and transmittance are indistinguishable for newborn and one-month old healthy babies, with limited or no differences between the age groups, gender, or left and right sides. The measurements made here are similar to other published results from neonatal intensive care unit (NICU) babies and healthy one-month-old babies in the 1000 to 3000 Hz range; there are differences among other studies at frequencies below 1000 Hz and above 3000 Hz. Possible reasons for these differences are discussed.

Keywords: middle ear; reflectance; newborn; hearing screening

Abbreviations: WBR Wide-band reflectance, NICU Neonatal intensive care unit, IRB Institutional Review Board, $R$ Power reflectance, $T$ Transmittance
1 Introduction

1.1 Overview and motivation for work

The diagnosis of middle-ear fluid in infants less than four to six months of age can be difficult because tympanometry is unreliable in these young ears (Holte, Margolis, & Cavanaugh, 1991). The long-term goal of this work is to determine if wide-band reflectance (WBR) measures (e.g., Keefe, Bulen, Arehart, & Burns, 1993; Voss & Allen, 1994; Allen, Jeng, & Levitt, 2005) can be used as objective measures to detect middle-ear fluid in infants, both at the time of newborn hearing screening and when middle-ear fluid is suspected in young ears. To date, WBR measures have not been reported on healthy, full-term, newborn babies; such measurements are the topic of this work.

One to three percent of newborn babies are referred for further audiological assessment at the time of their newborn hearing screening. Of these referrals, 90 percent are false-positives that can occur as a result of transient fluid or debris within the external or middle ear (Thompson et al., 2001; Doyle, Rodgers, Fujikawa, & Newman, 2000). The differentiation between transient loss associated with middle-ear fluid or debris and permanent conductive or sensorineural hearing loss is made via follow-up testing. In order to provide more complete audiological information starting at birth, a recent study funded jointly by the Centers for Disease Control and Prevention and the Association of Teachers of Preventative Medicine recommends the development of a screening tool for middle ear function at the time of newborn screening (Gravel et al., 2005).

In addition to helping diagnose newborn babies who refer during newborn hearing screenings, WBR measurements may also help diagnose and manage young infants with otitis media. Acute otitis media and otitis media with effusion affect 91 percent of children by age two (Paradise & Rockette, 1997); medical management of children who suffer from recurrent otitis media includes substantial efforts to evaluate their middle-ear air space for fluid, as this fluid leads to conductive hearing loss and increased risk for developmental delays (Gravel &
To determine the extent of fluid in the middle ear, clinicians rely on a combination of otoscopy, pneumatic otoscopy (which introduces ear-canal static pressure for the subjective judgement of tympanic-membrane mobility), air-conduction and bone-conduction audiograms, and tympanometry (Nozza, Bluestone, Kardatzke, & Bachman, 1992, 1994). With this set of diagnostic tests, it can sometimes be difficult to diagnose middle-ear fluid in children under six months of age. However, medical management of infants with middle-ear fluid is essential in order to ensure they develop language appropriately and don’t suffer from long-term effects of chronic otitis media. Thus, WBR based testing could be useful in following middle-ear fluid in babies under the age of six months, for which there currently exists no objective diagnostic test.

1.2 Wide band reflectance (WBR) measures

“Wide band reflectance” (WBR) measures refer to a group of quantities that can be used to represent the acoustic behavior of the ear. This term includes the related quantities: impedance, admittance, reflectance, transmittance, and power reflectance\(^1\). A method and equipment to measure these quantities exists (Allen, 1986; Keefe, Ling, & Bulen, 1992; Keefe et al., 1993; Voss & Allen, 1994). With this method, the Thévenin equivalent of a sound source and microphone system is measured using the system’s acoustic responses measured in a set of cavities or tubes. A single pressure measurement in a load such as an ear can then be used to calculate all of the WBR quantities.

For example, given the sound source’s Thévenin equivalent impedance \(Z_{TH}(f)\) and pressure \(P_{TH}(f)\), both functions of frequency \(f\), the impedance at the probe-tip location in the ear canal \(Z_{ear}(f)\) can be calculated via a pressure measurement \(P_{ear}(f)\) as

\[
Z_{ear}(f) = \frac{Z_{TH}(f)P_{ear}(f)}{P_{TH}(f) - P_{ear}(f)}.
\]

\(^1\)Power reflectance is a preferred term over the commonly employed term of energy reflectance. Power is the energy transfer per unit of time, whereas energy is measured over a specific time period.
Note, the admittance is the reciprocal of the impedance, and both the impedance and admittance are complex quantities with magnitudes and angles. From the impedance, the pressure reflectance is calculated as

\[ R(f) = \frac{Z_{\text{ear}}^N(f) - 1}{Z_{\text{ear}}^N(f) + 1}, \]  

where \( Z_{\text{ear}}^N(f) \) is the normalized impedance such that \( Z_{\text{ear}}^N(f) = \frac{Z_{\text{ear}}(f)}{\rho c} \) where \( \rho \) is the density of air, \( c \) is the speed of sound in air, and \( A \) is the cross-sectional area of the ear canal. The pressure reflectance \( R(f) \) is a complex quantity that can be interpreted as the ratio between the reflected pressure wave and the incident pressure wave within the ear canal. Inherent in this interpretation and equation is that there are no losses along the ear canal; measurements made on cadaver ears support this assumption (Voss, Horton, Woodbury, & Sheffield, 2008).

From the pressure reflectance \( R(f) \) we can compute a quantity called the power reflectance \( \mathcal{R} \), where

\[ \mathcal{R}(f) = |R(f)|^2. \]  

The power reflectance is a real number between 0 and 1, with \( \mathcal{R}(f) = 0 \) representing all power transmitted to the ear and with \( \mathcal{R}(f) = 1 \) representing all power reflected at the tympanic membrane back into the ear canal. Transmittance \( T(f) \) in units of dB is calculated from the power reflectance \( \mathcal{R}(f) \) as

\[ T(f) = 10 \log(1 - |\mathcal{R}(f)|^2). \]  

The transmittance is a useful quantity because its dB scale reduces the variability in power reflectance at the lower and higher frequencies and also provides a measure that might best relate to hearing levels (Allen et al., 2005), which would be useful and familiar to clinicians.

In this work, we present the WBR measures of power reflectance \( \mathcal{R} \) and transmittance \( T \).

1.3 Brief literature review

Significant changes occur in newborn outer and middle ears during the first six months of life. This includes an increase in size of both the ear-canal diameter and length and the middle-ear...
cavities, a change in the orientation of the tympanic membrane, a tightening of the ossicular joints connecting the ossicles, the formation of the bony ear-canal wall, and a decrease in the overall mass of the middle ear due to changes in bone density and loss of mesenchyme (Qi, Lui, Lufty, Funnell, & Daniel, 2006; Keefe et al., 1993; Saunders, Kaltenback, & Relkin, 1983). The ways in which these changes in newborn- and infant-ear anatomy affect WBR measurements at any given age are not fully understood; below, we review the current work related to WBR measures on newborn and infant ears.

WBR measurements have not been reported from a population of healthy, full-term normal hearing newborn babies, but prior WBR measurements have been made on neonatal intensive care unit (NICU) newborn babies and young healthy babies (Keefe et al., 1993, 2000; Shahnaz, 2008; Sanford & Feeney, 2008; Hunter, Tubaugh, Jackson, & Propes, 2008).

Keefe et al. (1993) conducted a study of 78 healthy babies ages one to 24 months in which they found systematic changes in reflectance with increasing age. They also found that middle-ear compliance is lower and middle-ear resistance is higher in infants than in adults, leading them to suggest that a substantial increase in ear-canal wall motion occurs at lower frequencies in young infants, which may account for the unreliability of 226 Hz tympanograms. Therefore, Keefe et al. (1993) recommends that impedance and reflectance measurements in the 2-4 kHz range could potentially be a useful clinical tool.

Keefe et al. (2000) conducted the first study of WBR measures in neonates. The study included 2081 neonates combined from three populations: neonates in neonatal intensive care units (NICU), neonates in well-baby nurseries, and neonates with one or more risk factors associated with hearing loss in well-baby nurseries. Keefe et al. (2000) found a median reflectance near 0.2 across all frequencies from 250 to 8000 Hz, and the middle 50 percent range varied with reflectance measurements from 0.1 to 0.3 with only modest variation with frequency. Keefe et al. (2000) also found significant differences between left and right ears and male and female ears for some frequency bands. They also found that changes as a function of conceptual age from 33 to 48 weeks were modest in comparison to age-related changes found
by Keefe et al. (1993). Additionally, reflectance measurements were found to be inconsistent
during the first 24 hours after birth; they suggested that the middle ear of one day olds might
differ from two to four day olds, presumably due to the presence of vernix and other material
in the external and middle ear that clears up in the first few days after birth. Keefe et al.
(2000) also highlight that a leak-proof seal (no air space between the ear tip and the ear-canal
wall) is vital in making accurate measurements (Keefe et al., 2000).

Shahnaz (2008) conducted a study of 26 NICU newborn babies with a mean gestational
age of 37.8 weeks and compared these data to power reflectance $R$ measurements taken from
there is a clear separation between NICU babies and adults below 727 Hz, with NICU babies
having lower $R$ values than adults. The NICU newborn mean $R$ from from Shahnaz (2008)
is larger at all frequencies than the corresponding mean for one-month old babies from Keefe

Hunter et al. (2008) conducted a study on 159 ears from 81 children age 3 days to 47
months; within this population 138 ears were classified as normal and 21 as abnormal. Con-
trary to previous conclusions drawn by Keefe et al. (1993) and Keefe et al. (2000) regarding
systematic changes with age, Hunter et al. (2008) found no significant age effect with respect
to reflectance measurements except at 6000 Hz. They also found no significant effects of ear
or gender.

Sanford and Feeney (2008) report power reflectance $R$ from 60 healthy full-term infants,
with 20 infants each aged 4 weeks, 12 weeks, and 24 weeks. These data were generally consis-
tent with the infant data from the study of Keefe et al. (1993), with some differences below
2000 Hz. Sanford and Feeney (2008) attribute the differences to the variation of methods used
to estimate infant cross-sectional ear-canal size, which is done through an acoustic estimate
in the study conducted by Keefe et al. (1993) and calculated using a set value based on the
diameter of calibration tubes (which were sized based on actual infant ear-canal diameters)
y by Sanford and Feeney (2008).
VanderWerff, Prieve, and Georgantas (2007) looked at test-retest reliability of wideband reflectance measures in 127 infants ages 2 weeks to 24 months. While the focus of this study was not on describing the reflectance parameterized by age, VanderWerff et al. (2007) showed the importance of an adequate probe fit for newborn babies where there is a leak-free seal, as the test-retest reliability in infants is only satisfactory when there a leak-free probe fit is present. They also found that compressible foam tips are significantly more effective than rubber probe tips in obtaining adequate test-retest reliability.

1.4 Goal of this work

This work characterizes the wide-band reflectance measures of power reflectance $R$ and transmittance $T$ of normal-hearing, healthy newborn babies. Keefe et al. (1993) demonstrated that power reflectance changes systematically with age, from one month past the age of two years. Other work focuses on power reflectance in NICU babies (e.g., Shahnaz, 2008; Keefe et al., 2000), babies one month and older (Sanford & Feeney, 2008; Keefe & Levi, 1996; Keefe et al., 1993), or groups that include a range of newborn to more than one month (Hunter et al., 2008). Here, we present WBR measures on normal-hearing, healthy newborn and one-month old babies. Ultimately, these types of normative measurements will be needed to develop a WBR metric to determine normal and abnormal WBR responses for different ages.

The specific goals of this study are: (1) To determine how WBR measures of power reflectance and transmittance vary as a function of age between newborn (age 3 to 5 days) and one-month old (age 28 to 34 days) infants, and (2) To characterize the normative range of power reflectance and transmittance in these populations.
2 Methods

2.1 Subjects and testing protocol

All measurements were approved by the Smith College Institutional Review Board (IRB), and all parents consented for their baby via an IRB approved consent form. The measurements reported here are from eight newborn (ages 3 to 5 days, 4 male and 4 female) and eleven one-month old (age 28 to 34 days, 7 male and 4 female) babies; one baby was included in both groups. Subjects were full-term (gestation age 40 ± 2 weeks), healthy babies who passed their newborn hearing screening. During a well-baby visit, each subject underwent an otoscopic examination to ensure a clear ear canal, and an ear-canal pressure measurement was made, from which WBR measures were calculated. Measurements were taken on both ears from 7 of 8 newborns and on 8 of 11 one-month olds. In other cases, one ear was not measured due to excessive wax, and three were not measured due to a noisy baby. Parents held their babies, and if the baby cried, he or she was encouraged to suck on a pacifier or nurse. The cord of the probe tip was held by the experimenter in order to maximize its stability.

2.2 Instrumentation

WBR measurements were made on newborn and one-month old babies using the FDA approved HearID system from Mimosa Acoustics (version 4.4.100.0) with an Etymotic ER-10c sound delivery system. To minimize acoustic leaks, foam tips (size 14B, Etymotic Research) were used (VanderWerff et al., 2007), and these tips were thinned out with scissors to allow them to fit into newborn ear canals. Two wideband sequential chirps stimuli at 70 dB SPL were produced from each of the two channels of the ER-10c, resulting in two consecutive and independent pressure measurements in each subject for each ear tested. For each channel, the average of \( N \) measurements is reported. Here the averaging time was 20.05 seconds (\( N = 470, \) with FFT length of 2048, a sampling rate of 48 kHz, and a frequency resolution of about 25 Hz). The artifact rejection was enabled so that bins measured in the presence of increased
background noise were rejected. Up to 60.03 seconds of data were collected to obtain the desired 470 bins for averaging. The software did not report the actual number of measurements obtained, but our qualitative sense is that most measurements reached the goal of 470.

2.3 Determination of the Thévenin equivalent and calculation of WBR measures

“Calibration” of the system refers to the measurements of the Thévenin equivalent $Z_{TH}$ and $P_{TH}$ of the ER-10c system, as described in the HearID manual. The calibration procedure was completed before measurements were made on each subject. Small variations in $Z_{TH}$ and $P_{TH}$ did occur over measurement sessions. While not documented here, these variations appear to depend on the orientation of the tip in the calibration cavities and not on real changes in the behavior of the system. An independent measurement of $Z_{TH}$ and $P_{TH}$ was made in a quiet laboratory setting. This independent measure approximates the median of all individual calibration measurements of $Z_{TH}$ and $P_{TH}$ (Merchant, 2009, Fig. 2-5). In order to reduce variability in reflectance measurements that would be introduced from variations in the calibration measurements of $Z_{TH}$ and $P_{TH}$, we calculate all WBR measures using these median $Z_{TH}$ and $P_{TH}$ measures.

The Thévenin equivalent of the system depends on the cross-sectional area of the cavity (or ear canal) to which the system is coupled. This area also affects the calculation of the reflectance (Eq. 2). Ideally, the diameter of the calibration tubes should approximate the diameter of the ear canal (Huang, Rosowski, Puria, & Peake, 2000). The HearID system is not directly set up to calibrate with a pediatric foam tip trimmed to a size to couple to a newborn ear canal. Therefore, we calibrated the system with the newborn sized (d=4.5mm) rubber tip and the corresponding smallest diameter HearID cavity set. Ear-canal measurements were made with the trimmed pediatric foam tip, and reflectance measures were calculated assuming an ear-canal diameter of 4.5mm.
2.4 Data analysis

The pressure measurement recorded from one of the two channels was analyzed for each ear. Channel A was selected as the default channel to be analyzed when the two channels were similar (Merchant, 2009, Appendix B shows measurements on both channels). Channel A was measured first and was chosen somewhat arbitrarily, with the reasoning that the baby was generally quieter when the experimenter chose to begin a measurement. However, in 12 of the 34 ears, channel B was analyzed instead of channel A; in two of the 12 cases the sound tube associated with channel A was visually seen to be blocked with debris after the measurements were made, and in ten of the 12 cases the phase response of the impedance calculated from channel B was substantially flatter with frequency at low frequencies than that calculated from channel A, suggesting a better acoustic seal on channel B. The observation that channel B was often associated with a better acoustic seal makes sense because the measurement on channel B was made several seconds later than that on channel A, allowing for more time for the foam tip to expand. We note that 18 of the 34 measurements were assessed to be equivalent for the two channels, 12 measurements were assessed to be superior on channel B and 4 superior on channel A (one probe filled with debris, one response consistent with the probe against ear-canal wall, and two impedance phase responses that were flatter at low frequencies on channel A as compared to channel B).

Pressures measured in the ear canal were smoothed using a 7-point moving average filter prior to computing WBR measures.

The reported p-values were computed with a permutation test with 10,000 iterations (Efron & Tibshirani, 1993) and replacement. For all analyses, all subject data were used, regardless of whether or not both ears were tested, with the exception of comparisons between the left and right ear, in which case only subjects with data collected on both ears was analyzed. No adjustment for multiple comparisons was made.
Figure 1 plots power reflectance (upper row) and transmittance (lower row) measurements on both newborn babies (left column) and one-month old babies (right column). The general patterns are similar for the two age groups. In both age groups, the median power reflectance is a maximum (near 0.6) at the lowest frequency plotted (500 Hz) and decreases with frequency until about 2000 Hz where it reaches a minimum that is near 0.11 for the newborn group and near 0.06 for the one-month old group. As frequency increases above 2000 Hz, the median power reflectance generally increases with frequency. The individual measurements are generally similar to the median's behavior with a few exceptions. In some cases there is more fine structure with additional minima and maxima across frequency. There is one right newborn ear with a much larger power reflectance than others, and one newborn ear that has a deep minimum near 900 Hz and a maximum just below 2000 Hz; there is one one-month old ear with a power reflectance that doesn’t decrease with frequency for frequencies below about 1500 Hz. Both age groups also have some ears with sharp maxima in the 4000-6000 Hz range. The transmittance is calculated directly from the power reflectance (Eq. 4), resulting in comparable similarities and differences between the age groups and the medians and individual ears. In both age groups, the median low-frequency transmittance increases with frequency from about -4 dB at 500 Hz up to a maximum value near 2000 Hz of -0.6 and -0.3 for the newborn and one-month old groups respectively. Above 2000 Hz, both medians generally decrease with increasing frequency. The transmittance shows the same outliers in the individual data as described above for the reflectance, highlighting that the median measurements are not always an accurate description of the individual measurements.

Figure 2 provides a direct comparison between the power reflectance (upper plot) and transmittance (middle plot) of newborn and one-month old babies. The medians for each group are plotted along with the population’s 25 to 75 percent range. The lower plot shows p values computed to test the null hypothesis that the two sets of data (newborn and one-month
old) come from different populations. At most frequencies, the power reflectance and transmittance are not significantly different between newborn and one-month old babies; however, near 2000 Hz it appears there could be differences between these populations, with the $p$ value dipping to about 0.02. A calculation of $p$ values was also made with two measurements removed to determine if the significance near 2000 Hz resulted from these two measurements that could be considered outliers. The newborn measurement from a right ear that is nearly 1 at 500 Hz and remains higher than all other measurements up to 3000 Hz was eliminated, and the one-month old measurement from a fHz was also eliminated (see Fig. 1). With these two measurements removed, the $p$ value calculated to test for differences in the two populations was much stronger near 2000 Hz with a $p$ value approaching 0.001 near 2000 Hz (thin dotted line in Fig. 2 lower). Thus, it appears there may be a difference in these two populations near 2000 Hz, but more measurements are needed to determine the significance of the difference.

Figure 3 compares the power reflectance and transmittance of male and female ears in both the newborn and one-month old babies. The medians for each group are plotted along with the population’s 25 to 75 percent range. The lower plot shows $p$ values computed to test the null hypothesis that the male and female ears come from different populations; the hypothesis is tested separately for newborn ears and one-month old ears. At essentially all frequencies, the power reflectance and transmittance are not significantly different between male and female babies; at the highest frequency (near 6000 Hz) the $p$ value for the newborn ears is suggestive of a difference between male and female ears; however, more measurements are needed to determine the significance of the difference. There are no significant differences in the one-month old population.

Figure 4 compares the power reflectance and transmittance of left and right ears in both the newborn and one-month old babies. The medians for each group are plotted along with the population’s 25 to 75 percent range. The lower plot shows $p$ values computed to test the null hypothesis that the left and right ears come from different populations; the hypothesis is tested separately for newborn ears and one-month old ears. The newborn ears have $p$ values
below 0.05 in narrow frequency bands near 1200 Hz and near 3000 Hz, and the one-month old ears don’t have any $p$ values consistent with left and right side differences. The significance of the newborn differences is not clear due to the small number of ears we have tested. We also note that the outlier right ear identified in the newborn measurements set above is not included here because no measurements were made on the left ear of the subject corresponding to the outlier right ear.
4 Discussion

4.1 Summary of data

Power reflectance and transmittance were calculated from pressure measurements made in the ear canals of newborn (3-5 days) and one-month-old (28-34 days) babies. Comparisons were made between the groups: age (newborn versus one month old), gender (female versus male), and ear side (left versus right). At most frequencies, there are no significant differences among these groups. For the age comparison, the unadjusted $p$ value dips below 0.02 in a narrow frequency band around 2000 Hz, suggesting a possible difference between the newborn and one-month old groups near 2000 Hz (Fig. 2). There are essentially no differences between the male and female ears at either newborn or one month of age (Fig. 3), with the exception of a possible difference in a very narrow frequency band near 6000 Hz. There are possible differences between newborn left and right ears in two frequency bands: near 1200 Hz and near 3000 Hz, and there are no signs of left versus right differences in the one-month-old babies (Fig. 4).

4.2 Comparison to other data

4.2.1 Other data

Figure 5 compares the power reflectance $R$ from this work to other measurements\(^2\). For frequencies below 3000 Hz, the median newborn $R$ from this work (purple solid triangles) is similar to the mean $R$ measured on NICU babies from Shahnaz (2008) (open gray triangles); above 3000 Hz the two data sets diverge with the Shahnaz (2008) $R$ approaching 0.6 and the $R$ measured here remaining below 0.4. The NICU median $R$ reported by Keefe et al. (2000) is substantially less than those from all other comparison measurements for frequencies at and below 1000 Hz; above 1000 Hz, the $R$ reported by Keefe et al. (2000) is generally similar to other measurements. This newborn population of Keefe et al. (2000) included NICU babies,\(^1\)

\(^2\)Data from (Hunter et al., 2008) are not included because their youngest population included ages 3 days to 2 months grouped together.
healthy newborns, and newborns at risk for hearing loss. The relatively low $R$ at and below 1000 Hz could indicate poor acoustic seals in some ears. Within their population, Keefe et al. (2000) found $R$ was larger in left ears as compared to right ears for frequencies below 1400 Hz; our results suggest a possible left-versus-right difference near 1400 Hz but in the opposite direction of the right ear having a larger $R$ than the left (Fig. 4, left column). Our results also suggest a potential difference between left and right ears near 3000 Hz; however, the small number of ears in our study prevents definitive conclusions regarding the significance of these trends. Keefe et al. (2000) also showed that below 2000 Hz, the male $R$ was larger than the female $R$. Our current study, which has both fewer ears and ears from only healthy babies, does not show these gender differences.

The median one-month-old $R$ from this work (green solid circles) is generally similar to the other measurements made on one-month-old babies for frequencies from 1000 to 6000 Hz. Below 1000 Hz, the $R$ from this work is higher than that from the other two studies: Sanford and Feeney (2008) and Keefe et al. (1993).

In summary, the power reflectance $R$ from this work is similar for newborn and one-month old ears and is also similar to most other published data.

Figure 5 also plots $R$ from a population of adult ears (Voss & Allen, 1994) in order to highlight the differences in $R$ between adult ears and young ears. Adult ears have a larger $R$ at most frequencies below about 3000 Hz, and in particular, on average, the $R$ from adult ears is substantially larger than from infant ears at both the lowest frequencies (500 Hz here) and in a frequency band around 2000 Hz.

### 4.2.2 Methodological differences

Additional factors are possible explanations for differences in reflectance measurements between this study and other published work. No other study has a population of healthy newborns compared to a population of healthy one-month olds, as these age ranges are either grouped together or healthy newborns are mixed with NICU and at-risk newborns. As a
result, there is no set of data available for exact comparisons to this study and population
differences could account for some variation.

Methodological differences between the current study and other published data could also
result in variations. VanderWerff et al. (2007) showed significant differences in test-retest
reliability between rubber and foam probe tips, and they show that rubber tips have poor
test-retest reliability in comparison to foam tips. During the methodological development
of the current study, we also found that rubber tips had a tendency to fall out and that it
was very difficult to obtain a leak-free seal using them. Rubber tips were used in two of the
published studies (Shahnaz, 2008; Hunter et al., 2008) while the probe tips used in the other
three studies (Keefe et al., 1993, 2000; Sanford & Feeney, 2008) are unknown.

The calculation of energy reflectance depends on the cross-sectional area of the ear-canal
(Eq. 2). Huang et al. (2000) show that accurate WBR measurements require that the Thévenin
equivalents of the acoustic measurement system be determined with loads that have
diameters within 10-15% of the actual ear-canal diameter. The Mimosa Acoustics System
[used in this study and also by Shahnaz (2008) and Hunter et al. (2008)] estimates the cross-
sectional area of the ear-canal based on the probe tip diameter and the calibration cavity
used during calibrations. With this system the cross-sectional area is either estimated to be
4.5mm (rubber-tip cavity) or 7.5mm (foam-tip cavity), as described in the Methods. Newborn
ear-canal diameters have been found to have diameters of about 4.4 mm (Qi et al., 2006;
Keefe et al., 1993), therefore calibrations using Mimosa’s “rubber-tip cavities” (used here)
are appropriate. However, use of the foam tip and corresponding cavity during calibrations
would result in a cavity diameter mismatch greater than the 10-15% recommended by (Huang
et al., 2000). Numerical simulations that explore the effects of variations in ear-canal cross-
sectional area show that for our newborn and one-month-old ears, increases in the cross-
sectional area increases $\mathcal{R}$ at most frequencies. Thus, it is possible that differences between
our measurements and those of others in Fig. 5 are partially a result of different definitions
of ear-canal cross-sectional area. While Keefe et al. (1993), Keefe et al. (2000), and Sanford
and Feeney (2008) do not use the Mimosa System, estimations of the cross-sectional area of
the ear canal from these studies could also result in variations. Sanford and Feeney (2008)
calculate reflectance with an estimated ear-canal area diameter of 4.8 mm. Keefe et al.
(1993) and Keefe et al. (2000) use an acoustic estimate made from the measured impedance
measurement, and this acoustic estimate has been shown to be inaccurate in some cadaver
ears (Voss et al., 2008). Thus, variations in ear-canal cross-sectional area estimates may
account for some of the variability among published reflectance measurements; thus, in order
to compare various studies, it is important to report the cross-sectional area used in calculating
reflectance measures.

Finally, in the hours after birth, the reflectance can be influenced by “debris” – for example,
the presence of vernix or amniotic fluid in the ear canal or mesenchyme or amniotic fluid in
the middle ear. Keefe et al. (2000) make qualitative arguments based on their large data
set that are consistent with ears less than 24 hours old differing from 24 to 72 hour-old ears
in that the younger ears have, on average, somewhat higher reflectances. While the times
at which various debris types disappear have not been clearly documented, the Keefe et al.
(2000) interpretation suggests that there may be a significantly higher percentage of ears filled
with debris within the first 24 hours of life than a few days later. Thus, while none of the
infants in this study were tested within 48 hours of birth, it is possible that due to individual
variation there was still left over debris in some subjects. It is also possible that subjects in
published studies may be affected by residual debris.

4.3 Clinical application and significance

Overall, this study has demonstrated that the WBR measures of power reflectance and trans-
mittance are essentially the same in healthy, normal-hearing newborn and one-month-old
babies. While WBR measures could lead to a clinical tool for the assessment of middle-ear
status and fluid in newborn and young babies, a normative data set showing changes (if
any) across small age increments in normal populations is necessary. This work adds norma-
tive measurements on normal hearing newborn babies to the other normative measurements available and summarized in Fig. 5. Future work will need to provide both (1) more WBR measurements in healthy newborn and infant populations to improve the normative database and (2) WBR measurements on ears with fluid for comparison to normal ears. Ultimately, comparison between normal and fluid-filled ears will lead to determination of the efficacy of WBR measurements to monitor and detect fluid in newborn and infant ears.
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References


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1 Power reflectance (upper row) and transmittance (lower row) measurements for left (blue) and right (red) ears, medians (black), and 25 to 75 percent ranges (gray shaded region) measured on 8 newborn (left column) and 11 one-month old (right column) healthy babies. Measurements on both ears were obtained for 7 of the 8 newborns and for 8 of the 11 one-month olds. The dotted lines indicate the measurements from the one subject with measurements in both age groups (left and right as a newborn and only left as a one-month old).

2 Summaries of the power reflectance (upper) and transmittance (middle) for the newborn ears (purple) and the one-month old ears (green). Solid lines indicate median measurements and shaded regions indicate the 25 to 75 percent ranges for each age population. All tested ears (left and right) were included. The lower plot shows the unadjusted p values from tests of the null hypotheses that there is no difference in the power reflectance or transmittance between the newborn and one-month old ears. The thin dotted line represents the p value computed to test for differences in power reflectance with two “outlier” measurements not includes; specifically, from Fig. 1, the eliminated measurements were the right ear of a newborn that is nearly 1 at 500 Hz and remains higher than all other measurements up to 3000 Hz and the right ear of a one-month old that has a power reflectance near 0.6 up to about 1500 Hz.

3 Summaries of the power reflectance (upper) and transmittance (middle) for female (pink) and male (cyan) newborn ears (left column) and one-month old ears (right column). Solid lines indicate median measurements and shaded regions indicate the 25 to 75 percent ranges for each age population. All tested ears (left and right) were included. The lower plot shows the unadjusted p values from tests of the null hypotheses that there is no difference in the power reflectance or transmittance between the female and male ears for each population.

4 Summaries of the power reflectance (upper) and transmittance (middle) for left (blue) and right (red) newborn ears (left column) and one-month old ears (right column). Solid lines indicate median measurements and shaded regions indicate the 25 to 75 percent ranges for each age population. Only data corresponding to subjects on which both right and left ears were measured were used here. The lower plot shows the unadjusted p values from tests of the null hypotheses that there is no difference in the power reflectance or transmittance between the right and left ears for each population.
The median power reflectances measured on newborn (purple) and one-month old (green) babies are plotted in comparison with data reported by Shahnaz (2008) (mean babies in a NICU), Keefe et al. (2000) (median data from NICU, healthy, and at-risk for hearing loss babies at 39 to 40 weeks conceptional age), Sanford and Feeney (2008) (healthy one-month olds), and Keefe et al. (1993) (healthy one-month olds). To increase visibility, measurements from this work and from Shahnaz (2008) have symbols spaced at every 15 data points, whereas the data from Keefe et al. (1993), Keefe et al., (2000), and Sanford and Feeney (2008) have symbols at every data point. Also plotted is the mean and 25 to 75 percent range from 24 adult ears (12 subjects) measured by Voss et al. (2009).
Newborn Ears

One-month Ears

Power Reflectance

Transmittance (dB)

Frequency (Hz)
Figure showing the relationship between frequency and power reflectance/transmittance for newborn and one-month ears. The graphs depict data for both female and male ears, with annotations indicating the number of ears in each group.