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Research paper

Longitudinal development of wideband reflectance tympanometry in normal and at-risk infants☆

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ABSTRACT

Purpose: The goals of this study were to measure normal characteristics of ambient and tympanometric wideband acoustic reflectance, which was parameterized by absorbance and group delay, in newborns cared for in well-baby and Neonatal Intensive Care Unit (NICU) nurseries, and to characterize the normal development of reflectance over the first year after birth in a group of infants with clinically normal hearing status followed longitudinally from birth to one year of age.
Methods: Infants were recruited from a well-baby and NICU nursery, passed newborn otoacoustic emissions (OAE) and automated auditory brainstem response (ABR) tests as well as follow-up diagnostic ABR and audiometry. They were tested longitudinally for up to one year using a wideband middle ear acoustic test battery consisting of tympanometry and ambient-pressure tests. Results were analyzed for ambient reflectance across frequency and tympanometric reflectance across frequency and pressure.
Results: Wideband absorbance and group delay showed large effects of age in the first 6 months. Immature absorbance and group delay patterns were apparent in the low frequencies at birth and one month, but changed substantially to a more adult-like pattern by age 6 months for both ambient and tympanometric variables. Area and length of the ear canal estimated acoustically increased up to age 1 year. Effects of race (African American and others compared to Caucasian) were found in combination with age effects. Mean and confidence intervals are provided for use as a normative longitudinal database for newborns and infants up to one year of age, for both well-baby and NICU infants.

1. Introduction

Acoustic ear-canal measurements in the human external ear canal can be used to describe normal function and development of the middle ear, as well as abnormal function. The ear canal and middle ear are immature at birth and undergo substantial and complex anatomical and physiologic development, especially during the first several months after birth. Anatomical development alters acoustic immittance measurements across the frequency range, due to concomitant changes in mechanical properties of mass, stiffness and resistance (Holte et al., 1991). Major anatomical and physical post-natal development of the ear canal includes increased diameter and length, altered orientation (Ikui et al., 1997) and increased rigidity due to gradual ossification of the medial bony portion (Eby and Nadol, 1986). The TM thins as mesenchymal tissue is resorbed (Ruah et al., 1991). The middle ear cavity increases after birth in aeration and size, and the mastoid air cells pneumatize; these factors increase both the physical volume of the middle-ear cavity as well as the acoustical compliance (Cinamon, 2009). After birth, the middle ear is not immediately aerated, and may contain amniotic fluid and other debris (Palva et al., 1999). By the

List of Abbreviations: ABR, auditory brainstem response; CI, confidence interval; DPOAE, distortion product otoacoustic emission; HP, high pass; LP, low pass; LS, least squares; NHS, newborn hearing screening; NICU, neonatal intensive care unit; SNR, signal to noise ratio; TEOAE, Transient evoked otoacoustic emissions; TM, tympanic membrane; TPP, tympanometric peak pressure; TW, tympanometric width; VRA, visual reinforcement audiometry; WAI, Wideband acoustic immittance

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end of the first 24 h after birth, approximately 50% of ears retain middle-ear effusion, decreasing to 27% after 48 h of age and 13% after 2 weeks of age (Roberts et al., 1995). The ossicles become less dense over the first six 6 months after birth as mesenchyme dissipates and ossification occurs, and the ossicular joints stiffen (Saunders et al., 1983; Eby and Nadol, 1986).

These anatomic changes are associated with physiological changes in the function of the infant middle ear compared to the adult ear. Accordingly, tympanometry measures reveal lower static admittance, broader tympanometric width, an appearance of notching at 0.226 kHz, and less energy transmission in frequencies above 1 kHz in newborns that appear related to physical ear canal flaccidity (Holte et al., 1990; Keefe and Levi, 1996). In neonate ears with middle-ear fluid, 0.226-kHz tympanograms are not reliably different from those obtained from normal ears (Paradise et al., 1976; Marchant et al., 1986). Higher frequencies from 0.66 to 1 kHz are better able to detect middle ear fluid than at the standard 0.226 kHz probe (Hunter and Margolis, 1992; Baldwin, 2006; Zhiqi et al., 2010). Variability in conventional tympanometry features in young infants has led to conflicting interpretations of what tympanometric criteria define a normal infant middle ear, and cast doubt on the accuracy and validity of tympanometry for newborn ears.

Wideband acoustic immittance (WAI) provides a means to study physiologic development. WAI is a family of middle ear acoustical measures that use click stimuli, analyzed across a broad frequency range (0.2–8 kHz), and may also include reflectance variables and acoustic stapedial reflex (ASR) responses in addition to admittance or impedance variables (Keefe et al., 1992; Feeney et al., 2013; Rosowski et al., 2013).

For an incident sound propagating in the ear canal in a forward direction towards the eardrum, the pressure reflectance at the probe microphone is the complex ratio (i.e., magnitude and phase) of the reverse-directed pressure at the microphone to its forward-directed sound pressure at the microphone. In this one-dimensional representation of sound transmission in the ear canal, this reverse-directed sound is generated by the reflection of the forward wave from the eardrum. The energy reflectance is the corresponding ratio of reflected sound energy to incident sound energy, and is equal to the squared magnitude of the pressure reflectance. Assuming that the sound energy in the ear canal is predominantly absorbed by the middle ear at the eardrum, the absorbance is the ratio of absorbed sound energy to incident energy, and is equal to one minus the energy reflectance. Although either quantity may be used, absorbance is used in the present study rather than energy reflectance inasmuch as absorbance is a measure of how much energy is absorbed by the middle ear. The latter energy is an upper bound to the energy that is ultimately delivered to the cochlea. The (reflectance) group delay is defined as the negative gradient of the pressure reflectance phase with respect to the frequency of sound (divided by a factor of 2π).

Wideband absorbance can be measured across frequency at ambient pressure in the ear canal and also as a function of varying air pressure in the form of a wideband absorbance tympanogram (Keefe and Levi, 1996; Margolis et al., 1999). A corresponding wideband group delay may also be measured under ambient and tympanometric conditions. Because middle-ear pressure has a large influence on absorbance at different frequencies, normal and abnormal characteristics of wideband tympanometry are needed across the age range.

Most reports of WAI in infants have used magnitude measures (energy reflectance or absorbance) obtained at ambient pressure, and have been cross-sectional studies, without confirmation of clinically normal hearing status. The largest changes in ambient energy reflectance in infants relative to adults occur below 0.5 kHz and above 2 kHz between 1 and 6 months of age (Aithal et al., 2014; Keefe et al., 1993; Shahnaz et al., 2014). There is up to a 30% change in mean energy reflectance and admittance magnitude from 0.25 to 0.75 kHz between 4 and 24 weeks of age (Sanford and Feeney, 2008). Changes are less apparent from 0.75 to 2 kHz, while developmental changes from 2 to 6 kHz are complex (Sanford and Feeney, 2008). Since the rate of post-natal maturation of the ear canal and middle ear is substantial during the first few months of life and ambient aural acoustic measures do not directly account for middle ear middle ear pressure effects, more information is needed to understand longitudinal developmental effects on pressurized WAI measures. Infants cared for in well-baby nurseries who did not pass newborn hearing screening show significantly greater energy reflectance (or less absorbance) in the frequency region from 1 to 4 kHz compared to infants who pass newborn screening (Sanford et al., 2009; Hunter et al., 2010; Aithal et al., 2015). Similar results have been reported in infants tested in a neonatal intensive care unit (NICU) (Shahnaz, 2008). Wideband absorbance or energy reflectance is able to predict middle ear dysfunction (Keefe et al., 2003) and conductive hearing loss in infants (Prieve et al., 2013).

The age range from birth to one year is a critically important developmental period that has clinical implications for detection of middle-ear dysfunction relative to newborn hearing screening. There have been no reported measurements of group delay in infants, thus data are needed to evaluate whether group delay measurements are feasible in young infants, and whether group delay conveys clinically relevant information. Measures of absorbance and group delay may help to better understand the functional changes with age that bear upon clinical diagnosis of sensorineural compared to conductive hearing loss.

The goals of this study were: (1) to measure the normal characteristics of ambient and tympanometric reflectance, which was parameterized in terms of absorbance and group delay, in newborns cared for in well-baby and NICU nurseries, and (2) to characterize normal development of wideband ambient and tympanometric reflectance over the first year after birth in a group of infants with clinically normal hearing status from birth to one year of age.

2. Material and methods

2.1. Subject enrollment

This study was part of a prospective, longitudinal project on translational wideband acoustic tests developed for identification of middle-ear, cochlear and neural hearing loss in infants, children and adults. Infants were enrolled after they received Newborn Hearing Screening (NHS) tests in normal and NICU nurseries at two urban hospitals in Cincinnati, Ohio: Good Samaritan Hospital (GSH) and Cincinnati Children's Hospital (CCHMC). The NHS protocol for the normal newborn nursery consisted of screening of all infants using Transient Evoked Otoacoustic Emissions (TEOAE, clicks at 80 dB SPL). If the infant did not pass TEOAE in either ear, Automated Auditory Brainstem Response (ABR, clicks at 35 dB nHL) was completed before hospital discharge.

A WAI test battery was composed of ambient and tympanometric wideband absorbance and group delay, and wideband acoustic stapedial reflexes. The WAI tests were measured after enrollment, on the same or the next day after the NHS exam, and over the first year after birth at follow-up study visits (1, 6, 9, 12 mo.) in which other tests were also completed. These other tests included threshold Tone-Burst ABR (TB-ABR), Distortion Product OAE (DPOAE) and Visual Reinforced Audiometry (VRA). The protocol used in this study was approved by the Institutional Review Boards of Cincinnati Children's Hospital Medical Center (CCHMC)

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