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How Does the Sound Pressure Generated by Circumaural, Supra-aural, and Insert Earphones Differ for Adult and Infant Ears?

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Abstract

Objective: To determine how the ear-canal sound pressure levels generated by circumaural, spuraaural, and insert earphones differ when coupled to the normal adult and infant ear.

Design: The ratio between the sound pressure generated in an adult ear and an infant ear was calculated for three types of earphones: a circumaural earphone (Natus Medical, ALGO with Flexicoupler™), a supraaural earphone (Telephonics, TDH-49 with MXAR cushion), and an insert earphone placed in the ear canal (Etymōtic Research, ER-3A). The calculations are based on (1) previously published measurements of ear-canal impedances in adult and infant (ages 1, 3, 6, 12, 24 months) ears [Keefe *et al.*, 1993, *J. Acoust. Soc. Am.*, **94**, 2617-2638.], (2) measurements of the Thévenin equivalent for each earphone configuration, and (3) acoustic models of the ear canal and external ear.

Results: Sound-pressure levels depend on the ear-canal location at which they are measured. For pressures at the earphone: (1) Circumaural and supraaural earphones produce changes between infant and adult ears that are less than 3 dB at all frequencies, and (2) Insert earphones produce infant pressures that are up to 15 dB greater than adult pressures. For pressures at the tympanic membrane: (1) Circumaural and supraaural earphones produce infant pressures that are within 2 dB of adult ears at frequencies below 2000 Hz and that are 5-7 dB smaller in infant ears than adult ears above 2000 Hz, and (2) Insert earphones produce pressures that are 5 to 8 dB larger in infant ears than adult ears across all audiometric frequencies.

Conclusions: Sound pressures generated by all earphone types (circumaural, supraaural, and insert) depend on the dimensions of the ear canal and on the impedance of the ear at the tympanic membrane (e.g., infant versus adult). Specific conclusions depend upon the location along the ear canal at which the changes between adult and infant ears are referenced (i.e., the earphone's output location or the tympanic membrane). With circumaural and supraaural earphones, the relatively large volume of air within the cuff of the earphone dominates the

acoustic load that these earphones must drive, and differences in sound pressure generated in infant and adult ears are generally smaller than those with the insert earphone in which the changes in ear-canal dimensions and impedance at the tympanic membrane have a bigger effect on the load the earphone must drive.

1 Introduction

The screening of hearing in newborn infants (e.g., American Academy of Pediatrics Task Force on Newborn and Infant Hearing, 1999; Thompson, McPhillips, Davis et al., 2001) has brought new attention to audiologic services for patients under two years of age. Hearing screening, assessment, and provision of amplification must all account for the acoustic differences between infant ear-canal dimensions and impedance and adult ears. The work presented here examines how differences between infant and adult ears influence the sound pressure level (SPL) generated by earphones during hearing screening and assessment. Specifically, a quantitative measurement-based model is developed for how the SPL generated by specific earphones used in hearing assessment differs between infant and adult ears.

The sound pressure generated by an earphone depends on two broad factors: (1) characteristics of the earphone itself and (2) characteristics of the ear to which the earphone is coupled. Consider a garden hose as an analogy to an earphone, where both the garden hose and the earphone generate a pressure (i.e., water pressure versus SPL). The water pressure at the end of the garden hose depends on: (1) the characteristics of the hose itself, such as its diameter, and (2) the characteristics of how the hose is coupled to the outside world, such as a nozzle or a narrow hole formed by a thumb at the delivery end of the hose. Thus, the water source's output depends on features of the source itself and features of how it couples to the outside world. Sources of sound (earphones) and electricity (e.g., batteries) also behave in this way. The sound pressure at the output of a loudspeaker will be different with a small rigid cavity enclosing its output than with it "loaded" by a football stadium. Similarly, the sound pressure generated by a given earphone might differ when the earphone is coupled to a relatively large adult sized ear versus a smaller infant ear.

While it is generally recognized that an infant ear presents a different acoustic load to an earphone than an adult ear, the current literature does not provide a quantitative evaluation for how and when infant ears affect earphone output, relative to adult ears. Much of the work reported in this area has focused on the difference in the SPL in infant ears with hearing aids and the measured SPL of that hearing aid in a standard 2cc coupler (e.g., Feigin, Kopun, Stelmachowicz, & Gorga, 1989; Seewald, Hudson, Gagne, & Zelisko, 1992; The Pediatric Working Group of the Conference on Amplification for Children with Auditory Deficits, 1996; Tharpe, Sladen, Huta, & Rothpletz, 2001; Bagatto, Scollie, Seewald, Moodie, & Hoover, 2002). Recommendations for real-ear measurement of hearing aid output have been made in order to calculate a "real-ear coupler difference" (RECD) for a child that can be used instead of repeated probe microphone measurements in the fitting of amplification. Recently, it has also been demonstrated experimentally that the RECD measured with an insert earphone may differ from an RECD that would correspond to a hearing instrument (e.g., hearing aid receiver), because the RECD depends on the impedance of the sound source (Munro & Toal, 2005).

Some attention has also been given to determining the SPL produced by an earphone during hearing screening and assessment. The Pediatric Working Group of the Conference on Amplification for Children with Auditory Deficits (1996) recommends testing thresholds in infants and young children with insert earphones because the child's RECD can be applied to compensate for differences between real-ear SPLs and the earphone's output. Johnson and Nelson (1991) demonstrate that a click stimulus delivered from an insert earphone has a higher-frequency emphasis in an infant ear as compared to an adult ear, and they recommend that this difference should be considered when using the Auditory Brainstem Response to evaluate infant hearing. Seewald and Scollie (1999) estimate how the SPL output of different transducers is affected by the nine-month-old ear, and they highlight the importance of considering how infant ears differ from adult ears. Thus, there is a need to determine how SPLs differ between infant and adult ears so that the appropriate corrections can be made during hearing screening and assessment.

During hearing tests, including infant screening and assessment, sound-pressure levels generated in the ear canal are not generally measured. Instead, it is assumed that the earphone's calibration (sound pressure output per volt input) is effectively independent of the acoustic properties of the ear being tested (Burkhard & Corliss, 1954; Shaw, 1974; Borton, Nolen, Luks, & Meline, 1989; Wilber, 1994; Voss, Rosowski, Merchant, Thornton, Shera, & Peake, 2000; Voss, Rosowski, Shera, & Peake, 2000), regardless of the dimensions of the ear (e.g., adult versus infant ears), which can significantly alter the acoustic properties of the ear (i.e., its acoustic impedance). Acoustic properties of transducers coupled to any ear can be understood more clearly using acoustic models with components that vary according to the ear of interest. Voss and colleagues (Voss, Rosowski, Shera, & Peake, 2000; Voss, Rosowski, Merchant, Thornton et al., 2000) demonstrate the use of such a model and provide a detailed analyses of how both supraaural and insert earphone responses are affected by a variety of middle-ear disorders. Specifically, it is demonstrated that in many cases when the ear's impedance differs from normal (e.g., mastoid surgery, tympanic membrane perforations, tympanostomy tubes), the sound pressure generated by an earphone differs systematically from its expected value. A similar model can be applied to the newborn testing situation to quantify the SPLs generated by a variety of earphones. The goal of this work is to quantify how earphone responses are affected by infant ears relative to normal adult ears. In particular, we consider three commonly used earphones: (1) a circumaural earphone (Natus Medical, ALGO with Flexicoupler™) used to measure ABR responses in infant hearing screening, (2) a standard audiometric supraaural earphone (Telephonics, TDH-49 with MXAR cushion), and (3) an insert earphone (Etymōtic Research, ER-3A).

2 Methods

2.1 Approach

Any earphone system can be characterized by an ideal sound pressure source P_S in combination with a source impedance Z_S (Møller, Hammershøi, Jensen, & Sørensen, 1995; Voss, Rosowski, Shera, & Peake, 2000). In the electrical engineering subject of circuit theory, this source characterization is known as a source's Thévenin equivalent (e.g., Hayt & Kemmerly, 1986), and this approach has been widely used to characterize acoustic sources in auditory science (Flanders, 1932; Møller, 1960; Rabinowitz, 1981; Allen, 1986; Keefe, Ling, & Bulen, 1992; Voss & Allen, 1994; Lynch, Peake, & Rosowski, 1994; Huang, Rosowski, Flandermeyer, Lynch, & Peake, 1997; Neely & Gorga, 1998; Voss, Rosowski, Shera, & Peake, 2000; Voss, Rosowski, Merchant, & Peake, 2000). Through the Thévenin representation, it is straight forward to understand how various ears or "loads" affect the output of an earphone.

Figure 1 provides a circuit model representation of an earphone coupled to a load, where the load could be an ear. The pressure that the source actually produces at its output – that is the pressure at the load – can be expressed as

$$P_{OUT} = \frac{1}{1 + \frac{Z_S}{Z_L}} P_S, \tag{1}$$

where P_{OUT} is the pressure produced by the earphone (for example, in the ear), Z_S is the source impedance, P_S is the source's ideal pressure source representation, and Z_L is the impedance of the load to which the earphone is coupled. For a given earphone, Z_S is constant and does not change. Equation 1 provides a quantitative description for how the sound pressure generated by an earphone depends on the load (or ear): Variations in the output pressure of an earphone that result from variations in the acoustic properties of the load (e.g., ear) connected to it are entirely dependent on the ratio Z_S/Z_L.

To determine how age-related variations in the impedance of the external and middle ears affect the sound pressure generated in the external ear, we use acoustic measurements to characterize each earphone (i.e., circumaural, supraaural, insert) by its Thévenin equivalent (i.e, P_S and Z_S). Next, we combine a model for the external ear with measurements of the ear's impedance made in the ear canal to determine the acoustic loads driven by each earphone, with age as a parameter. We use these models in combination with each earphone's Thévenin equivalent to predict how the pressure generated in the external ear and along the ear canal differs between infants aged one to 24 months relative to an adult ear.

2.2 Source and impedance characterization for earphones: Thévenin equivalents

Characterization of a sound source by a source pressure and impedance (Thévenin equivalent) is a common and well documented procedure (Flanders, 1932; Allen, 1986; Keefe et al., 1992; Voss & Allen, 1994; Lynch et al., 1994; Huang et al., 1997; Neely & Gorga, 1998; Voss, Rosowski, Shera,

& Peake, 2000; Voss, Rosowski, Merchant, & Peake, 2000). The Thévenin source impedance Z_S for the circumaural earphone is measured here and that for the supraaural and insert earphones were already measured by Voss, Rosowski, Shera, and Peake (2000). These Thévenin impedances are used, in conjunction with measurements of the ear's impedance, to calculate, from Eq. 1, the pressure that each earphone generates in the external ears of adults and infants.

Measurement of the Thévenin equivalent of an earphone requires a sound assembly that contains both a sound source and a microphone. Here, the Thévenin equivalent of the transducer (sound source and microphone) used to drive the ALGO earphone and Flexicoupler™system (Natus Medical, Inc) was determined via pressure measurements made in cylindrical tubes (Fig. 2). Pressure measurements in three of the tubes provided three complex equations for the two unknown Thévenin equivalents, Z_S and P_S. Acoustic estimates of the tube lengths were obtained by minimizing the error function in the over-determined system of three equations (e.g., Allen, 1986; Keefe et al., 1992; Voss & Allen, 1994), and the optimized lengths were used to compute Z_S and P_S. Results were checked by comparing measured and theoretical impedances in four additional tubes. At frequencies in the range 200 to 8000 Hz the measured impedances were within 1 dB in magnitude and 0.01 cycles in angle of the corresponding theoretical impedances, except at maxima and minima in the impedance, where the estimates depend heavily on the precise length of the tube; at these frequencies the differences approached 5 dB in magnitude and 0.05 cycles in angle.

The Thévenin impedances for the three earphone systems studied here (circumaural, supraaural, insert earphones) are plotted in Fig. 3. For each earphone system, it is this impedance that is used to characterize the source with its Thévenin impedance Z_{TH} in Fig. 4.

2.3 Models for ears coupled to earphones

2.3.1 Overview

In this section we describe the acoustic models for each earphone coupling to the ear (Fig. 4). First we describe model elements and parameters that are common to more than one of the earphones. We follow this section by describing features that are specific to individual earphone types. We note that there are three major components for the coupling of each earphone to an ear:

1. Representation of the earphone itself (i.e., P_S and Z_S in Fig. 1).

2. Representation of the coupling of the earphone to the ear, which in the cases of the supraaural and circumaural earphones includes the volume of air within the earphone cuff, the pinna and the concha. The representation of the coupling of the earphone is part of Z_L in Fig. 1.

3. Representation of the ear canal and impedance at the tympanic membrane, which is also part of Z_L in Fig. 1.

The origins for how the model component values were selected for each of the earphone models are described below and summarized in Tables 1 and 2. The acoustic load on the earphone, Z_L from Fig. 1, includes the coupling of the earphone to the ear, the ear canal, and the impedance of the ear at the tympanic membrane.

2.3.2 Model elements and parameters common to all earphone types

We consider three locations along the ear canal for this analysis and we define subscripts that refer to acoustic variables at these locations: (1) The entrance to the ear canal within the concha corresponds to the external-ear location $_{EE}$, (2) The location within the ear canal at which the leading-edge of the insert earphone sits (i.e., where the sound comes out of the insert earphone) corresponds to the ear-canal location $_{EC}$, and (3) The location of the tympanic membrane corresponds to tympanic membrane location $_{TM}$. Corresponding acoustic variables of pressure P, volume velocity U, and impedance Z exist at these locations. For example, P_{EE}, P_{EC}, and P_{TM} refer to the SPL at the entrance to the ear canal, at the insert-earphone location, and at the tympanic membrane, respectively.

All models (Fig. 4) include a representation of the ear canal terminated by the impedance at the tympanic membrane. The ear canal is modeled as a rigid cylindrical tube with length and diameter a function of age (Table 2). The impedance at the tympanic membrane, Z_{TM}, is derived from measurements of ear impedance at the location of the insert earphone, Z_{EC}, on infants (ages 1, 3, 6, 12, and 24 months) and adults made by Keefe, Bulen, Arehart, and Burns (1993).

The pressure at the measurement location of Keefe et al. (1993) P_{EC} and the pressure at the tympanic membrane P_{TM} (Fig. 4) are related by the transfer matrix

$$\begin{pmatrix} P_{\mathrm{EC}} \\ U_{\mathrm{EC}} \end{pmatrix} = \begin{pmatrix} \cosh(ikl_{EC2TM}) & Z_{\mathrm{o}} \sinh(ikl_{EC2TM}) \\ 1/Z_{\mathrm{o}} \sinh(ikl_{EC2TM}) & \cosh(ikl_{EC2TM}) \end{pmatrix} \begin{pmatrix} P_{\mathrm{TM}} \\ U_{\mathrm{TM}} \end{pmatrix}, \tag{2}$$

where U_{EC} is the volume velocity of air within the ear canal at the measurement location of Keefe et al. (1993), U_{TM} is the volume velocity of air at the tympanic membrane, $Z_{\mathrm{o}} = \rho c/A$ is the characteristic impedance of the tube representing the ear canal, l_{EC2TM} is the distance from the insert earphone (i.e., measurement location of Keefe et al. (1993)) to the tympanic membrane, A is the cross-sectional area of the tube representing the ear canal, $k = 2\pi f/c$ is the wavenumber, $i = \sqrt{-1}$, ρ is the density of air, c is the velocity of sound in air, and f is the frequency (e.g., Møller, 1965; Rabinowitz, 1981; Lynch et al., 1994; Huang et al., 1997; Voss, Rosowski, Merchant, & Peake, 2000; Voss & Shera, 2004). Values for these parameters related to ear-canal dimensions are found in Table 2 and are from the measurements of Keefe and Bulen (1994). With Eq. 2, the impedance at the tympanic membrane can be computed as $Z_{TM} = P_{TM}/U_{TM}$, with $Z_{EC} = P_{EC}/U_{EC}$ the measured ear impedance from Keefe et al. (1993). Figure 5 shows the Z_{EC} measured by Keefe et al. (1993) and the corresponding Z_{TM} computed via Eq. 2.

In a similar fashion to Eq. 2, for the circumaural and supraaural earphones we can relate the acoustic variables at the entrance to the ear canal (represented by $_{EE}$) to the variables at the tympanic membrane. The pressures P_{EE} and P_{TM} are related by the transfer matrix

$$\begin{pmatrix} P_{\mathrm{EE}} \\ U_{\mathrm{EE}} \end{pmatrix} = \begin{pmatrix} \cosh(ikl_{EE2TM}) & Z_{\mathrm{o}} \sinh(ikl_{EE2TM}) \\ 1/Z_{\mathrm{o}} \sinh(ikl_{EE2TM}) & \cosh(ikl_{EE2TM}) \end{pmatrix} \begin{pmatrix} P_{\mathrm{TM}} \\ U_{\mathrm{TM}} \end{pmatrix}, \tag{3}$$

where U_{EE} is the volume velocity of air at the concha, l_{EE2TM} is the ear-canal length (Table 2), and all other variables are defined above with the description of Eq. 2.

For both the circumaural and supraaural earphones, there are substantial volumes of air contained within the concha and under the earphone cuffs. In these cases, the volumes are modeled by compliances with equivalent volumes equal to the volume of air in the relevant space. The acoustic compliance C is related to the volume V as

$$C = \frac{V}{\rho c^2} \tag{4}$$

where ρ is the density of air and c is the speed of sound in air.

[Table 1 near here.]

[Table 2 near here.]

2.3.3 Circumaural earphone

The circumaural earphone (Natus Medical, ALGO with Flexicoupler™) couples to the infant ear via a disposable circumaural coupler (Flexicoupler™) that fits over the entire pinna and adheres to the skull (Fig. 4 upper-left). The volume of the Flexicoupler™is 14 cm^3, as measured by filling it with water with a calibrated syringe. The effective acoustic volume of the Flexicoupler™– the volume within the Flexicoupler™that the earphone must drive – is the volume of the Flexicoupler™minus the volume of the pinna within the Flexicoupler™. Here, we estimate the volume of the pinna of an adult ear[1] to be 5 cm^3, resulting in an effective Flexicoupler™volume of 9 cm^3. This estimate provides an upper bound on the infant pinna volume (5 cm^3) and a lower bound on the air volume within the Flexicoupler™when coupled to the infant ear (9 cm^3). Thus, we model the connection of the circumaural earphone to the ear canal as a volume of 9 cm^3 of air, which can be represented as an acoustic compliance (Eq. 4) and is labeled C_{cuff} within the model (Fig. 4 upper circuit). (A sensitivity analysis that demonstrates the effects of a range of volumes is presented in the Appendix.) Connected to the volume of air within the Flexicoupler™is the ear canal and the rest of the auditory system. We note that we assume that the entire concha volume is included within the volume of 9 cm^3 under the circumaural Flexicoupler™. The ear canal is modeled as a cylindrical tube between the entrance of the ear canal and the tympanic membrane (Eq. 3).

2.3.4 Supraaural earphone

The supraaural earphone (Telephonics, TDH-49 with MXAR cushion) couples directly to the pinna (Fig. 4 upper-center). The total volume within the external ear is the sum of the volumes of air within the supraaural earphone cuff ($7\,\mathrm{cm}^3$, as measured by Voss, Rosowski, Shera, and Peake (2000)) and the volume within the concha (Table 2). This external-ear volume is represented in the model as the compliance C_{cuff}, which is calculated from the total air volume with Eq. 4.

2.3.5 Insert earphone

The insert earphone (Etymōtic Research, ER-3A) couples directly into the ear canal with a foam plug (Fig. 4 upper-right). The acoustic variables for the insert earphone are related through Eq. 2.

3 Results

Using the models of Fig. 4, we calculate the sound pressure generated by each earphone coupled to infant ears (ages 1, 3, 6, 12, and 24 months) and an adult ear at three locations: (1) The external ear (P_{EE}) for the circumaural and supraaural earphones, (2) Mid-canal at the location of an insert earphone (P_{EC}) for all three earphones, and (3) At the tympanic membrane (P_{TM}) for all three earphones. For each case, the pressure is normalized by the pressure corresponding to that in the adult ear (i.e., P_{EE}^{adult}, P_{EC}^{adult} P_{TM}^{adult}). Specifically, we define ΔP as the ratio (in dB) between the pressure generated in a given ear normalized by the pressure generated in the adult ear,

$$\Delta P_x = 20 \log \frac{P_x}{P_x^{adult}}, \tag{5}$$

where x refers to one of the relevant pressures (i.e., $_{EE}$, $_{EC}$, $_{TM}$) and ΔP_x depends on frequency, C_{cuff}, ear-canal length, ear-canal cross-sectional area, and impedance of the ear. These parameters are summarized in Tables 1 and 2.

Fig. 6 plots, for each age, all relevant ΔP_x for the three earphones. With the circumaural earphone, the changes between infant and adult sound pressures generated in the external ear

(ΔP_{EE}), at the output of the earphone, differs between infant and adult ears by less than 2 dB from 125 to 8000 Hz. Similarly, with the supraaural earphone, the adult and infant pressures at the earphone output differ by a maximum of 3 dB.

Differences between the adult and infant pressures are greater at other ear-canal locations. Infant-to-adult pressures at the location of the insert earphone output, ΔP_{EC}, differ among earphone types. For the circumaural and supraaural earphones, ΔP_{EC} is within a few dB of zero at frequencies below 4000 Hz and approaches five dB between 4000 and 8000 Hz. The insert earphone response has infant-to-adult ratios of up to 8 dB at frequencies below 2000 Hz and up to 15 dB above 2000 Hz; these ratios decrease systematically toward zero dB as age increases.

The infant-to-adult pressure ratio at the tympanic membrane, ΔP_{TM}, also depends on earphone type. For the circumaural and supraaural earphones, ΔP_{TM} is within a few dB of zero at frequencies below 2000 Hz, and above 2000 Hz ΔP_{TM} exhibits a local minimum up to -7 dB near 3000 Hz, above which ΔP_{TM} increases towards zero. Thus, with the circumaural and supraaural earphones, the pressure at the tympanic membrane is smaller in infant ears than in adult ears at the higher audiometric frequencies. In contrast, the pressure at the tympanic membrane with an insert earphone is always greater in an infant ear than in an adult ear. In this case, ΔP_{TM} is between 5 and 10 dB across the audiometric frequencies for the youngest ears, and ΔP_{TM} approaches zero dB as age increases.

4 Discussion

4.1 Summary of results

Figure 6 shows that the pressures generated by earphones differ in adult and infant ears, and the specific differences depend both on the location of pressure reference (e.g., external ear, ear canal, tympanic membrane) as well as the type of earphone. At the tympanic membrane, with the circumaural and supraaural earphones, the ratio between infant and adult pressures ΔP_{TM} is within a few dB of zero at frequencies below 2000 Hz and as much as -7 dB at higher frequencies. For insert earphones, the ratio ΔP_{TM} is 5 to 8 dB across all audiometric frequencies at one month of age and decreases systematically toward zero (adult-like) as age increases from one month to 24 months.

4.2 Effects of ear-canal dimensions and impedance at the tympanic membrane

Section II-C-1 describes how the SPL generated by an earphone depends on (1) properties of the earphone itself, (2) the manner in which the earphone couples to the ear, (3) and the anatomical properties of the ear canal (length and diameter) and the impedance at the tympanic membrane. Here, we determine how variations in the ear canal dimensions and the impedance at the tympanic membrane affect the ear-canal SPL.

The model results of Fig. 6 assume average values for the impedances and dimensions of ears of different ages. Here, we examine how changes from these average values affect our model predictions (Fig. 7). Specifically, we consider variations in three quantities: (1) Diameter of the ear canal, (2) length of the ear canal, and (3) impedance magnitude at the tympanic membrane. For the two ear-canal dimensions – length and diameter – we vary the specific quantity's value from 0.8 times the average value to 1.2 times the average value, in incremental steps of .05 times the average value; we chose this range of 0.8 to 1.2 because it represents a range that allows overlap between one or two age groups but generally not more than two age groups (Table 2). For the impedance magnitude at the tympanic membrane we vary the specific quantity's value from 0.3 to 3 in incremental steps of 0.1, which is approximately a $\pm$ 10 dB range from the average values. We chose this large a range because it allows the impedances measured at each age (Fig. 5) to overlap with one another so that we can determine qualitatively the contributions of ear-canal effects versus impedance at the tympanic membrane on the pressure generated in the ear canal.

Figure 7 shows how the pressure generated at the tympanic membrane is influenced by these three quantities (impedance at the tympanic membrane, ear-canal diameter, and ear-canal length) for each earphone type. For each earphone, the sound pressure changes ΔP_{TM} from the average adult ear are plotted for the one-month old ear, the 24-month old ear, and the adult ear.

In each case, changes are plotted for variations in the average diameter only (left column, black), simultaneous variations in length and diameters (left column, gray), variations in impedance magnitude only (right column, black), and variations in all three quantities (right column, gray). For each of the four combinations, the extreme pressure range possible with the varied quantity (maximum and minimum) is the entire range shaded within Fig. 7.

Variations of 0.8 to 1.2 times the average ear-canal diameter (black shaded region of right column for each earphone of Fig. 7) lead to variations in P_{TM} of less than four dB (relative to the average ear-canal lengths) at all frequencies for all earphones and all ages. The greatest sensitivity to ear-canal diameter is with the insert earphone at frequencies above 2000 Hz, where changes from average dimensions approach four dB.

Variations of 0.8 to 1.2 times both the average ear-canal diameter and the ear-canal length (gray shaded region of right column for each earphone of Fig. 7) demonstrate that: (1) Below about 4000 Hz, variations in ear-canal length have minimal effects on the SPL produced by any of the earphones coupled to any of the ears, and (2) above 4000 Hz, the ear-canal length contributes about an additional 5 dB of variability in the SPL at the tympanic membrane for all of the earphones at most of the ages.

Variations of 0.3 to 3 times the average impedance magnitude at the tympanic membrane (black shaded region of left column for each earphone of Fig. 7) shows that the impedance at the tympanic membrane has different effects on the SPL generated by the circumaural and supraaural earphones as compared to the insert earphone. For the circumaural and supraaural earphones, below 1000 Hz the impedance at the tympanic membrane has minimal effects on the SPL ($\pm$ 1 dB) and above 1000 Hz the effects are as much as $\pm$ 5 dB for some ages at some frequencies. In contrast, with the insert earphone, the impedance at the tympanic membrane has $\pm$ 5 dB effects on the SPL for all ages and all frequencies up to 4000 Hz and above 4000 Hz the effect of impedance variations is smaller and depends on age.

In summary, the SPL generated at the tympanic membrane by any earphone is influenced by both the ear-canal dimensions and the impedance at the tympanic membrane. For the circumaural and supraaural earphones, the SPL is within a few dB of the average adult ear for frequencies up to 1000 Hz, and at higher frequencies there can be variations of up to ± 10 dB. For the insert earphone, the SPL can vary by ± 5 dB from the average adult ear for frequencies up to 1000 Hz, and at higher frequencies there can be variations of up to ± 15 dB.

4.3 Pressures at low frequencies (less than 2000 Hz)

For frequencies below 2000 Hz and at all ear canal locations, the circumaural and supraaural earphone responses are similar for infant and adult ears but the insert earphone response is substantially different for infant and adult ears (Fig. 6). In the cases of the circumaural and supraaural earphones, Fig. 7 shows that at these lower frequencies, the impedance at the tympanic membrane has minimal effects on the ear-canal SPL; in these cases, the fractional changes with age in the volume contained within the cuff of the earphone and ear canal are small; for both infant and adult ears, the circumaural and supraaural earphones drive a relatively large volume of air that is minimally affected by the dimensions of the ear canal[2]. In contrast, the insert earphone drives only the air volume within part of the ear canal and the rest of the ear. In this case, changes in ear-canal dimensions and changes in the impedance at the tympanic membrane result in substantial changes to the acoustic load that the earphone must drive, resulting in relatively large changes in the output of the earphone between infant and adult ears.

4.4 Pressures at high frequencies (above 2000 Hz)

For frequencies above 2000 Hz, there are generally larger pressure variations between the infant and adult ears than at the lower frequencies (Fig. 6). One exception is for the circumaural and supraaural earphone outputs at the entrance to the ear canal, where the air volume within the external ear and the earphone itself dominates the acoustic load to the earphone. At this location, ratios between infant and adult ears are less than 3 dB. At the other two locations – mid ear canal and tympanic membrane – larger ratios exist between the pressures generated in the infant and adult ears. For the circumaural and supraaural earphones, there is a minimum in ΔP_{EC} of about -3 dB near 3000 Hz, followed by a maximum of about 5 dB near 6000 Hz. Similarly, there is a minimum in ΔP_{TM} that is as much as -7 dB near 3000 Hz and then ΔP_{TM} increases toward zero as frequency increases. The behavior of both ΔP_{EC} and ΔP_{TM} for the circumaural and supraaural earphones results primarily from the differences in length of the adult and infant ear canals. In the adult ear, there is a pressure maximum at the ear-canal quarter-wavelength frequency of about 3500 Hz; this maximum in the pressure in the adult ear produces a minimum in the ratios ΔP_{EC} and ΔP_{TM} because the maximum in the adult ear canal pressure is in the denominator of these ratios.

4.5 Model results versus real-ear measurements

4.5.1 Model approach

The results presented here are from a measurement-based model. A similar measurement-based model was developed by Voss, Rosowski, Shera, and Peake (2000) to compare the sound pressures generated by earphones in normal adult ears with pressures generated in adult ears with specific middle-ear pathologies (mastoid bowls, perforations, tympanostomy tubes). In this case, corresponding real-ear measurements were made on subjects with normal ears and with the middle-ear pathologies that were modeled (Voss, Rosowski, Merchant, Thornton et al., 2000), and the real-ear measurements and model predictions showed excellent agreement. The agreement between the real-ear measurements (Voss, Rosowski, Merchant, Thornton et al., 2000) and the corresponding model (Voss, Rosowski, Shera, & Peake, 2000) support the assumption that the modeling approach used in this work is valid.

4.5.2 Model assumptions

The modeling approach applied here assumes that the ear-canal can be represented as a rigid cylindrical tube. In fact, it is know that the ear canal is not a cylinder and that infant ear-canal walls are more elastic than adult ear-canal walls. Stinson (1985) and Stinson and Lawton (1989) demonstrate that the uniform cylindrical model for the ear canal is reasonable for frequencies below 6000 to 8000 Hz in adult ears. At these lower frequencies, the wavelength of sound is much larger than any ear-canal dimensions and specific features of the ear canal are not important.

Since the infant ear canal is smaller than the adult ear canal, the frequency limit for which infant ears can be approximated by a cylindrical model would be higher than that for adult ears. Thus, we expect our cylindrical model of the ear canal to be reasonable for both infant and adult ears up to at least 6000 Hz.

A second model assumption is that the ear-canal walls can be approximated by rigid walls. There is evidence that the ear-canal walls of young infants (younger than four months of age) might differ from the ear-canal walls of older infants and adults (Holte, Margolis, & Cavanaugh, 1991; Keefe et al., 1993); however, these differences are not well understood (Keefe et al., 1993, pp.2628-2629). If the younger ear canals are more compliant than the older ear canals, as is postulated (Holte et al., 1991; Keefe et al., 1993), then this additional compliance can be thought of as additional ear-canal volume. Such an additional ear-canal volume would most likely be very small relative to the diameter of the ear canal, and its effects would be much smaller than the effects of diameter changes demonstrated in Fig. 7. In summary, we expect that errors introduced by modeling the ear-canal walls by rigid walls are negligible.

4.6 Clinical Implications

4.6.1 General considerations

The work presented here demonstrates that the effects of variations in ear-canal dimensions and ear impedance on the sound-pressure output of earphones coupled to infant ears are not the same for all earphone types. Additionally, at many frequencies, the earphone's output differs between the location of the earphone and the tympanic membrane. This difference is not typically considered when using earphones calibrated according to the ANSI standards. Calibration of audiometric earphones assumes a standard transfer function between the calibration cavities and the ears under test. The ANSI standards for earphone calibration in audiometers states:

> Inclusive of all other allowed deviations, the sound pressure level produced by the earphone(s) shall differ by no more than 3 dB from the indicated value at test frequencies from 125 through 5000 Hz and by no more than 5 dB at 6000 Hz and

higher (American National Standard Institute, 2004).

Based on this calibration standard, pressure variations at the tympanic membrane of up to 3 dB below 5000 Hz and 5 dB above 5000 Hz would be considered acceptable. For insert earphones the pressure variations in one-month old ears compared to adult ears exceed this acceptable range. For circumaural and supraaural earphones, the range of pressure variations is acceptable below 2000 Hz and above 5000 Hz. Only a narrow frequency band centered at 3000 Hz has variations greater than 3 dB.

In summary, if we consider the pressure produced in the one-month old ear at the tympanic membrane, then the difference between the infant ear and the adult ear which is assumed in earphone calibration exceeds the acceptable range. For circumaural and supraaural earphones, these calibration inaccuracies are only at 3000 and 4000 Hz, while for the insert earphones the calibration inaccuracies occur at all audiometric frequencies.

4.6.2 Infant hearing screening

The circumaural earphone (ALGO with Flexicoupler$^{\text{TM}}$) is used clinically in the measurement of auditory brainstem responses in conjunction with newborn hearing screening. For this earphone, at frequencies below 2000 Hz, the pressures generated at the infant tympanic membrane are within two to three dB of those generated at the adult tympanic membrane. Above 2000 Hz, the pressures generated at the infant tympanic membrane are up to 7 dB smaller than those generated at the adult tympanic membrane (Fig. 6). Thus the changes are in the direction of greater screening sensitivity because more babies with borderline hearing thresholds would refer rather than pass. This situation is in contrast to the statements of Norton, Khan, and Dolphin (2000) who suggest that the circumaural earphone would generate a pressure in an infant ear that is 10 to 20 dB greater than that generated in an adult ear.

In contrast to the circumaural earphone, the insert earphone generally produces a pressure in the infant ear that exceeds that produced in an adult ear. At the tympanic membrane, the pressure in the one-month-old ear is 5-8 dB larger than the adult ear at most audiometric frequencies. Thus, in screening situations an insert earphone would have reduced sensitivity in hearing loss detection.

Our analysis also indicates that, for accurate hearing screening, it is essential to connect any given hearing screening instrument to the ear using the instrument manufacture's quidelines. For example, Clark, Dybala, and Moushegian (1998) studied the sound pressures generated by a previous version of the ALGO system, but they exchanged the 14 cm^3 Flexicoupler™for alternative devices to couple the system to the ear, such as a foam plug designed for an insert earphone. Clark et al. (1998) concluded that it is essential to use the Flexicoupler™: the expected sound pressure is produced only when the 14 cm^3 Flexicoupler™supplied for use with the ALGO system by Natus Medical, Inc. is used and not when an alternative one of a different volume is used because the air volume within the Flexicoupler™contributes to the calibration and the functioning of the earphone. In fact, the use of an alternative coupling mechanism that provides a volume of air smaller than 14 cm^3 would result in an increase in the SPL generated in the ear canal. If an insert foam plug is coupled to the ALGO system, and the model of Fig. 4 is applied, the resulting ear-canal SPL is 20 dB (100 Hz) to 35 dB (6,000 Hz) in excess of the levels produced with the 14 cm^3 cuff designed for the system. Thus, it is absolutely essential that earphones calibrated outside of the ear are coupled to the ear in the manner that they are designed to be coupled: the calibration process relies on the coupling mechanisms.

4.6.3 Infant hearing screening and assessment

The acoustic models presented here also have implications for the outcomes of serial audiologic evaluations used to monitor hearing sensitivity in infancy. Figure 8 illustrates a hypothetical case of an infant subject with a stable, mild, sensorineural hearing loss. Using the same supraaural earphone, repeated audiologic test results on this subject, from age 1 month to adulthood, would be within 3 dB of the 30 dB hearing loss at all audiometric frequencies except 4000 Hz, where the result would indicate a loss of 33 to 36 dB. In contrast, Fig. 8 (Right) illustrates the same stable, mild, sensorineural hearing loss tested with insert earphones during the first 24 months of life without accounting for the differences in sound pressures generated by the insert earphone in the growing ear canal. In this case, the hearing thresholds appear up to 8 dB more sensitive than they actually are. Serial testing of hearing measured with inconsistent use of insert and supraaural earphones – using different earphones at different ages – without accounting for sound-pressure variations of insert earphones could give the impression of a fluctuating loss in the higher frequencies.

There is currently no ideal earphone for audiologic testing of infants. A standard audiologic supraaural earphone, such as the TDH 49 modeled in this paper, provides a more stable calibration over a wide range of ear-canal volumes and ear impedances, but it is more difficult to place on an infant ear and maintain position without ear canal collapse or acoustic leaks. Insert earphones have fewer problems with ear canal collapse and acoustic leaks but are harder to replace after becoming dislodged in sleeping children and have greater variation in sound pressure with varying ear-canal volumes and ear impedances. The adhesive circumaural phone tested was designed for newborn hearing screening (Herrmann, Thornton, & Joseph, 1995) to prevent the problems associated with the standard supraaural earphone, but in its current design it can not generate enough sound pressure for use in the measurement of elevated hearing thresholds, and is thus only available for infant screening applications.

4.6.4 Hearing assessment in general

The general finding from Fig. 7 demonstrates that substantial variability in ear-canal SPLs can occur in both infants and adults as a result of normal variations in ear-canal dimensions and ear impedance. This finding is consistent with reports of up to 40 dB of intersubject variability in ear-canal SPLs measured in large numbers of adult ear canals (Valente, Potts, Valente, Vass & Goebel, 1994; Valente, Potts, & Valente, 1997; Saunders & Morgan, 2003).

Whatever earphone is used in audiologic testing, the sound pressure differences associated with infant, adult, and pathological ear canals should be understood and incorporated into audiologic interpretation. Clearly, the traditional units of hearing level (HL) that are specified relative to the SPL in a coupler do not represent individual ear-canal SPLs. Such recommendations have been made for several years for insert earphones in infants (The Pediatric Working

Group of the Conference on Amplification for Children with Auditory Deficits, 1996; Feigin et al., 1989), but are often not used in actual clinical practice. Greater clinical consistency with insert phones would be attained if in-the-ear calibration procedures were incorporated into the design of all audiometric equipment especially when insert earphones are used not only for infants but also for ears with middle-ear pathology (Voss, Rosowski, Shera, & Peake, 2000; Voss, Rosowski, Merchant, Thornton et al., 2000).

5 Conclusions

Sound pressures generated by all earphone types (circumaural, supraaural, and insert) depend on the dimensions of the ear canal (e.g., infant versus adult) and the impedance at the tympanic membrane (e.g., infant versus adult). Specific conclusions depend upon the location along the ear canal at which the changes between adult and infant ears are referenced. For pressures generated at the earphone's location: (1) Ratios between pressures generated by circumaural and supraaural earphones in infant and adult ears are less than 3 dB at all frequencies, and (2) Ratios between pressures generated by insert earphones in infant and adult ears are as much as 15 dB. For pressures generated at the tympanic membrane: (1) Pressures generated by circumaural and supraaural earphones in infant ears are within 2 dB of that in adult ears at frequencies below 2000 Hz and are 2-7 dB smaller in infant ears than adult ears above 2000 Hz, and (2) Pressures generated by insert earphones are 5 to 8 dB larger in infant ears than adult ears across all audiometric frequencies. In general, the insert earphone generates a larger sound pressure in the infant ear relative to the adult ear because the infant ear canal has a smaller volume than the adult. With circumaural and supraaural earphones, the relatively large volume of air within the coupler or cuff of the earphone dominates the acoustic load that these earphones must drive, and differences in sound pressure generated in infant and adult ears are generally smaller than those with the insert earphone.

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Appendix: Sensitivity analysis for effects of external ear volume on circumaural earphone response

As described in the methods section, we estimate the volume of air within the circumaural cuff to be $9\,\mathrm{cm}^3$ for an adult ear, which is a lower bound on the volume of air for the volume within the cuff coupled to an infant ear. In other words, if the volume of air for the adult ear is $9\,\mathrm{cm}^3$, then the volume of air for the infant ear is between $9\,\mathrm{cm}^3$ and the total volume within the cuff of $14\,\mathrm{cm}^3$. Fig. 9 shows how different volume assumptions affect the sound pressure generated in the cuff of the circumaural earphone, where we plot ΔP_{EC}, the sound pressure generated in the infant ear with cuff air-volumes of 9 to $12\,\mathrm{cm}^3$ relative to sound pressure generated in the adult ear with a cuff volume of $9\,\mathrm{cm}^3$. (The calculations of Fig. 6 assume a cuff volume of $9\,\mathrm{cm}^3$ in both infants and adults.) The parameter in Fig. 9 is the pinna volume that varies inversely with cuff volume, such that pinna volume plus cuff volume equals $14\,\mathrm{cm}^3$. Therefore, a pinna volume of $5\,\mathrm{cm}^3$ corresponds to a cuff volume of $9\,\mathrm{cm}^3$, while a pinna volume of $2\,\mathrm{cm}^3$ corresponds to a cuff volume of $12\,\mathrm{cm}^3$.

Fig. 9 demonstrates how the sound pressure within the cuff of the circumaural earphone depends on the volume of air within the cuff. As the volume of the pinna decreases, the sound pressure generated decreases because the total volume of air within the cuff increases. However, at all frequencies, the changes in sound pressure relative to those in the adult ear are less than 3 dB. Thus, the sensitivity of the model calculations for the circumaural earphone in Fig. 6 (left) can be affected by up to about 3 dB for a realistic range of pinna volumes. Although the calculation is sensitive to the pinna volume used, the total change in sound pressure from the adult ear remains less than 3 dB. Thus, the actual sound pressure generated by the circumaural earphone within the cuff decreases as the pinna volume decreases. Depending on the volume of the infant's pinna, the sound pressure generated by the circumaural earphone in an infant ear may be a few dB smaller than that generated in an adult ear.

Notes

[1]The volume of the adult pinna was measured on one subject. A 200 ml beaker was filled with 200 ml of water, measured in a graduated cylinder. The subject placed her pinna into the beaker and a volume of water equal to the volume of the pinna was displaced out of the beaker. The remaining water in the beaker was poured back into the graduated cylinder and measured to be 195 ml. Thus, the volume of the pinna is estimated to be 5 ml or $5\,\mathrm{cm}^3$. It is possible that some of the air within the concha was also part of the $5\,\mathrm{cm}^3$ volume estimate, in which case the actual pinna volume would be smaller than our estimate; again, we report $5\,\mathrm{cm}^3$ as an upper bound.

[2]The quantitative change in the volume of air under the supraaural and circumaural earphone cuffs between the infant and adult ears is easily estimated. For the supraaural case, the entire external ear volume for the cuff is $7\mathrm{cm}^3$ for all ages (it is the physical volume within the earphone cuff) plus the concha volume, which ranges from $0.27\,\mathrm{cm}^3$ for a 1-month-old infant to $3.80\,\mathrm{cm}^3$ for an adult ear. Thus, the total air volume within the supraaural earphone for a 1-month-old infant is about 0.7 times that of an adult (i.e., about 3 dB smaller). For the circumaural case, no measurements of infant pinna volume are available. If we estimate a lower bound on infant pinna volume of $2\,\mathrm{cm}^3$ (Appendix) and the adult pinna volume as $5\,\mathrm{cm}^3$, then the infant volume is about 1.3 times that of the adult, or about 2.5 dB larger.

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Figure Captions

1. Electric-circuit analog that represents acoustic variables for an earphone coupled to an ear. The earphone is represented by a sound pressure source P_S in series with the source impedance Z_S (the earphone's Thévenin equivalent). The acoustic load on the earphone is labeled Z_L and could be an ear. The pressure P_{OUT} represents the pressure generated by the earphone at its ouput, possibly into the concha (circumaural or supraaural earphone) or ear canal (insert earphone). The labeled quantities are acoustic quantities with sound pressure analogous to voltage relative to ground and volume velocity analogous to current (i.e., the impedance analogy). The figure and caption are modified from Voss, Rosowski, Shera, and Peake (2000).

2. The ALGO (Natus Medical, Inc) transducer was coupled to seven cylindrical tubes of diameter 0.56 cm and responses to a chirp stimulus were measured. Responses in the tubes with lengths of 2.94 cm, 1.9 cm, and 1.31 cm were used to calculate the Thévenin equivalent, and responses in tubes with lengths of 3.56 cm, 2.34 cm, 1.67 cm, and 0.87 cm were used to check the Thévenin equivalent. (Measurements were made in seven of the ten tubes in the photograph.)

3. Thévenin impedance of the three earphone systems indicated in the legend. The impedance magnitudes of the circumaural earphone (ALGO) and the insert earphone (ER-3A) are larger than the that of the supraaural earphone (TDH-49) because the diaphragms in the ALGO and ER-3A earphones are substantially smaller in cross sectional area than in the TDH-49 earphone. The source impedances do not include the effects of the cuffs that couple either the circumaural or supraaural earphones to the ear; the cuffs are included in the model developed within Fig. 4. **Upper:** Magnitude (mks acoustic ohms) **Lower:** Angle (cycles).

4. Representations for how each earphone system couples to an ear. **Upper:** Schematics for how each earphone couples to the external ear. The earphone is indicated in black.

Lower: Analog circuit models for the ear coupled to the earphone. For the circumaural and supraaural cases, the entire ear canal is represented by the box labeled "Ear canal", and for the insert earphone, the portion of the ear canal between the insert earphone and the tympanic membrane is represented by the box labeled "Part of Ear canal". In both cases, the box representing the ear canal represents a cylindrical air-filled tube (Eqs. 2 and 3). For each case, the ear's impedance at the tympanic membrane is represented by the box labeled Z_{TM}, where Z_{TM} is determined from the impedance measurements of Keefe et al. (1993) and Equation 2. The circumaural earphone couples to the skull around the pinna and the airspace sealed under the earphone contains the entire pinna and concha as well as additional air space outside of the pinna. Similarly, the supraaural earphone couples to the pinna of the ear and the airspace sealed under the earphone contains air within the supraaural cuff and air within the concha. In both cases, this coupling is represented in the model as a compliance labeled C_{cuff} which represents the volume of air contained within the circumaural and supraaural earphone cuffs, respectively. The insert earphone sits within the ear canal and does not include an additional coupling air volume.

5. **Left:** Measurements of Z_{EC} from Keefe et al. (1993). **Right:** Estimates of Z_{TM} computed from Z_{EC} (Left column) and Eq. 2. **Upper:** Magnitude. **Lower:** Angle.

6. Ratio of the pressures generated by each earphone relative to that generated by the same earphone in an adult ear (i.e., 0 dB corresponds to the pressure generated in the adult ear). The parameter is age. **Left:** Circumaural. **Middle:** Supraaural. **Right:** Insert. **Upper:** P_{EE}, the pressure in the external ear at the output of the circumaural and supraaural earphones. **Middle:** P_{EC}, the pressure in the ear canal at the location of the output of the insert earphone. **Lower:** P_{TM}, the pressure at the tympanic membrane.

7. Sensitivity analysis to determine how variations in (1) Ear-canal diameter, (2) Ear-canal length, and (3) Impedance at the tympanic membrane affect the model predictions of SPL generated at the tympanic membrane, relative to an average adult ear, for the one-

month old (Upper), 24-month old (Middle), and adult (Lower) ears. Results from each earphone are indicated and grouped together with six plots (cirumaural, supraaural, and insert). For each earphone, the left column shows the effects of variations in the ear-canal diameter (solid black, labeled "Diameter") and variations in both the ear-canal diameter and length (solid gray, labeled "Diam/length"). The right column shows the effects of variations in the impedance at the tympanic membrane (solid black, labeled "Impedance") and variations in all three quantities of ear-canal length, diameter, and impedance (solid gray, labeled "Total"). The shaded regions indicate the range of SPL generated when the variable(s) under test were systematically varied. The ear-canal length and diameter were each varied from 0.8 to 1.2 times the average value, in steps of 0.05, and the impedance at the tympanic membrane was varied from 0.3 to 3 times the average value, in steps of 0.1. The pressure generated at the tympanic membrane for the indicated combinations of these three quantities was calculated, and the extreme pressure range (maximum and minimum) is the entire shaded range referred to in the legend.

8. Hypothetical case study of an infant with a stable, 30 dB flat sensorineural hearing loss at one month of age and no change in hearing status from one month to 24 months of age. **Left:** The hearing loss measured with a supraaural earphone. **Right:** The hearing loss measured with an insert earphone. As the subject ages from one to 24 months, the hearing loss appears to increase because the sound pressure output from the insert earphone changes. At one month of age the true hearing loss is underestimated because the earphone generates larger-than-expected sound-pressure levels.

9. A sensitivity analysis for how the circumaural earphone output depends on the pinna volume for a 1-month-old infant. Plotted is ΔP_{EC}, the ratio of the pressures generated at the earphone output by the circumaural earphone coupled to a one-month-old ear relative to that generated by the circumaural earphone coupled to an adult ear (i.e., 0 dB corresponds to the pressure generated in the adult ear). For all calculations, the pinna volume of the adult is assumed to be $5\,\mathrm{cm}^3$. The parameter for the one-month-old ear is pinna volume.