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Theoretical and Applied External Ear Acoustics

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Abstract

The external ear (pinna and earcanal) plays a major role in transforming acoustic signals from free field to the tympanic membrane in humans. It acts as a filter to reduce low frequencies, a resonator to enhance mid frequencies (2.0 to 7.0 kHz), and a direction-dependent filter at high frequencies to augment spatial perception. The external ear transfer function is altered by variations in the physical dimension of the external ear either due to individual differences or due to mechanical obstructions such as blockages, hearing aid placement, perforation of the tympanic membrane, and use of insert earphones. It is significant that any change in the characteristics of the acoustic signal can produce considerable disparity in within- and between-individual responses. The present paper examines published studies on sound pressure transfer function provided by the external ear in humans.

Key Words: Earcanal acoustics, external ear, external ear transfer function

In a natural listening situation, the external ear (the pinna and the earcanal) acts as a coupler between airborne sound and the middle ear (Shaw, 1966). Consequently, the characteristics of the sound reaching the middle ear from free field or earphone are influenced by the physical dimensions and the response properties of the external ear. In the past several years, there has been immense interest in specifying the acoustic characteristics of the external ear due to increased reliance on measurements made inside the earcanal for hearing aid fitting, earphone calibration, immittance measurements, high-frequency audiometry, otoacoustic emission testing, and auditory brainstem responses (ABRs). A potential confounding factor during earcanal measurement is the considerable variability in the acoustic response properties of the external ear across individuals. Understanding the functions of the external ear requires an appreciation of basic acoustics and the transformation properties of the external ear. This article provides a descriptive analysis of external ear transfer functions in humans.

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External Ear Pressure Transfer Function

The literature is replete with articles on acoustic properties of the external ear based on measurements made from the human earcanal, as well as data from mathematical and physical models (Wiener and Ross, 1946; Shaw, 1966, 1974 a, b, 1975, 1980; Shaw and Teranishi, 1968; Teranishi and Shaw 1968; Djupesland and Zwislocki, 1972; Mehrgardt and Mellert, 1977; Stinson et al, 1982; Khanna and Stinson, 1985; Gilman and Dirks, 1986; Rabbitt and Holmes, 1989; Rabbitt and Friedrich, 1991; Hellstrom and Axelsson, 1993; Stinson and Khanna, 1994). The most common measurement of earcanal function has been the magnitude of pressure difference (PT/PSF) between the sound pressure at the tympanic membrane (PT) compared to that in the sound field (PSF). According to Shaw (1975), the factors that govern the sound transformation from free field to the tympanic membrane can be divided into two major areas: (1) the head, torso, and pinna flange acting as diffracting bodies and (2) the concha and the earcanal acting as resonators.

In their classic study, Wiener and Ross (1946), placed a probe-tube microphone at two locations in the earcanal, one near the tympanic membrane and the other halfway between the tympanic membrane and the concha. They measured sound pressure level in the earcanal from freefield sound source located at 0°, 45°, and

90° in the horizontal plane. The pressure distribution in the earcanal across frequencies varied considerably; however, the most obvious pressure gain was reported in the region of 2.0 to 4.0 kHz (10–15 dB) with a maximum increment of 17 to 22 dB at 3.0 kHz.

The relationship between the external ear structures and the pressure gain was extensively investigated by Shaw and Teranishi (Shaw and Teranishi, 1968; Teranishi and Shaw, 1968; Shaw 1974b). In one of the studies, Teranishi and Shaw developed a physical model of the external ear using cylindrical cavities, which simulated the physical dimensions of structures such as the concha, pinna flange, and earcanal, to evaluate resonance properties. As these cavities were added, starting from concha to the earcanal, the resonance peaks systematically shifted from higher to lower frequencies, as shown in Figure 1. The most salient effect in the resonance peak was noted when the earcanal was added to the external ear replica (see Fig. 1C). Notably, the largest peak was at 3.0 kHz, which is in agreement with physical measurements and values obtained from mathematical computations.

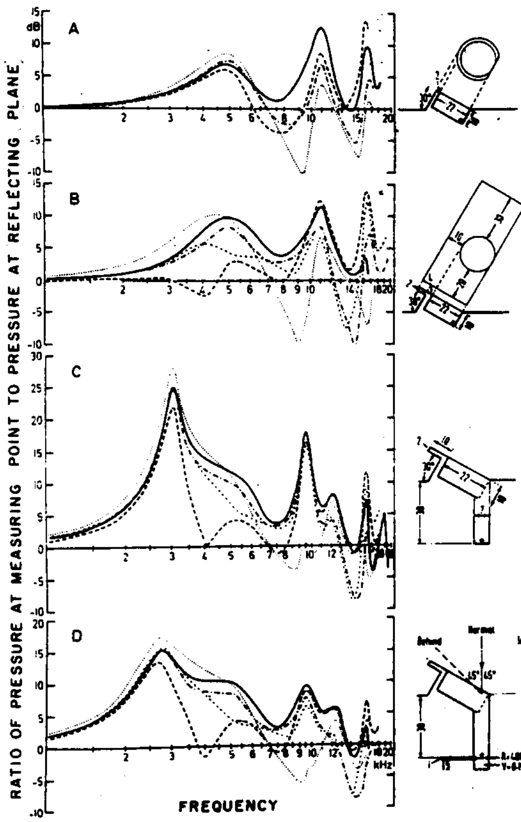

Figure 1 Effect of location of the sound source on response curves. Normal incidence (solid line), source at 45° azimuth (dotted line), behind (long dash), above (dot-dash), and below (short dash). *A*, response properties of concha; *B*, concha and pinna; *C*, earcanal added to A and B; *D*, combined effects of all of the components and tympanic membrane. (Reproduced with permission: Teranishi R, Shaw EAG. [1968]. External ear acoustic models with simple geometry. *J Acoust Soc Am* 44:258. Copyright 1968 American Institute of Physics.)

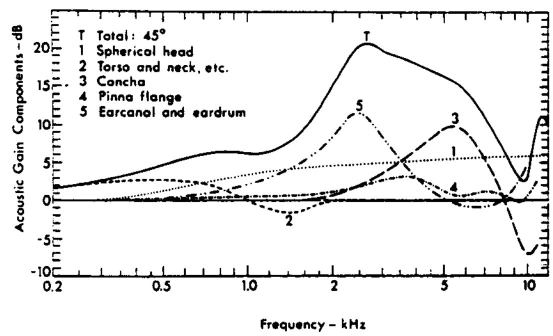

Figure 2 Average pressure gain from various structures for a sound presented at 45° azimuth. (Reproduced with permission: Shaw EAG. [1974]. The external ear. In: Keidel WD, Neff WD, eds. *Handbook of Sensory Physiology (Vol. 1)*. New York: Springer-Verlag, 468. Copyright 1974 Springer-Verlag.)

A classic description of the contributions of various structures was provided by Shaw (1974a). He suggested that the total pressure, "T," shown in Figure 2 is the resultant sum of the contributions of several structures: the torso, the neck, the head, the pinna flange, the concha, and the earcanal. The contribution of each structure is based on the interaction between size of the structure and the wave length (λ) of the sound. Therefore, for frequencies below 1.0 kHz, the gain in sound pressure is 5 dB or less, mostly due to the contributions of the torso, neck, and head. At frequencies between 1.0 kHz and 3.0 kHz, however, the earcanal is the single contributor, and the gain in sound pressure may be as high as 20 dB. Above 3.0 kHz, small structures, such as the concha, provide the pressure gain. Thus, the sound reaching the tympanic membrane reflects the cumulative effect of the pressure gain attained by individual components and is reported to be 15 to 20 dB between 1.5 to 7.0 kHz (see T curve in Fig. 2). In summary, the external ear filters the lower frequencies and amplifies mid frequencies to improve signal-to-noise ratio.

It is evident from the above studies that most of the resonance effect has been attributed to the contribution of the earcanal. An earcanal is essentially a tube that is open at one end (concha region) and closed at the other (tympanic membrane). The air inside this tube acts as a resonating body. When the frequency of the sound matches the natural resonant frequency of the earcanal, the sound pressure is enhanced at that frequency. The natural resonant frequency of the earcanal is four times its length (25-mm average adult earcanal length), indicating that only one-quarter of the wave can fit into the tube at any one pass. Thus, the earcanal is called a quarter-wave resonator. For wavelengths of lower frequencies, the quarter-wave length is longer than the length of the earcanal (25 mm). The opposite is true for higher frequencies. Theoretically, one can calculate the resonant frequency of the earcanal by the formula $f = c/4*l$, in which f = resonant frequency of the earcanal, c = velocity of sound in air (34,400 cm), and l = length of the earcanal (25 mm). Given the values of the velocity of the sound in air and the length of the earcanal, one can determine the resonant frequency of the earcanal as follows:

$$f = 34400/(4 \times 2.5).$$

The resonant frequency in this example, where the length of the earcanal is 25 mm, is 3.4 kHz.

External Ear Contributions to Spatial Perception

The location of the sound source can vary either in horizontal (interaural) or vertical (above or below) directions, and a combination of these two directions can produce spatial patterns in which the sound may originate from several locations in the auditory space. Studies have indicated that the earcanal pressure gain across frequencies is direction dependent, that is, the earcanal gain varies with the direction of source for high-frequency sounds (Shaw, 1974a, b; Middlebrooks et al, 1989; Musicant et al, 1990; Hellstrom and Axelsson, 1993). Most of the earlier studies in humans investigated the directional pressure sensitivity in the earcanal in the horizontal plane (Wiener and Ross, 1946; Shaw, 1974a, b). However, some of the recent measurements of pressure gain have demonstrated a large dependence on horizontal and vertical locations on the ear's response to tones of different frequencies (Musicant et al, 1990 [in cats]; Middlebrooks et al, 1989; Hellstrom and Axelsson, 1993 [in humans]).

A quantitative measurement of the direction-dependent pressure differences in the earcanal was examined by Hellstrom and Axelsson (1993). They measured the transfer function (microphone placed 1–3 mm from the tympanic membrane) from free field to the tympanic membrane in 19 subjects for sounds (⅓-octave band-filtered noise from 0.2 to 20.0 kHz) presented through speakers located at 24 horizontal (azimuths 0° to 315°) and 3 vertical (+45° E, 00° E, -45° E) positions, for a total of 72 positions. The averaged results across subjects from eight azimuthal (azimuths 0° to 315° in 45°) and three vertical (+45° E, 00° E, -45° E) locations are illustrated in Figure 3, a–h. The ordinate in Figure 3 is the pressure gain in the earcanal compared to the sound field, and the abscissa refers to the frequency of the stimuli (0.2–20 kHz). The most prominent finding from these curves is that the direction-related differences in the sound pressure gain occur at frequencies above the resonant frequency of the earcanal. These findings are in agreement with earlier studies of Shaw and Villancourt (1985) (see dotted line in Fig. 3). They reported that direction-dependent pressure differences were greater than 20 dB across subjects at certain frequencies (between 6.3 and 10 kHz), and that variations can be as much as 30 dB in

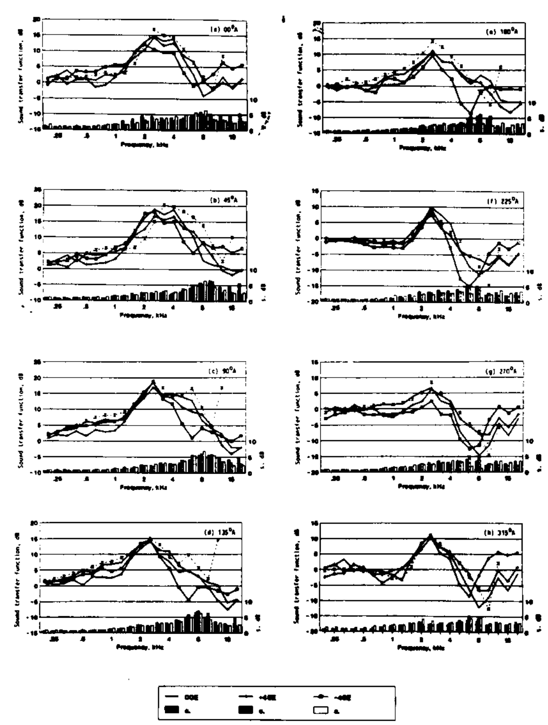

Figure 3 Sound pressure transfer function from free field to tympanic membrane. Sections a–h sound pressure measured inside the earcanal for sounds presented at eight horizontal and three vertical locations. (Reproduced with permission: Hellstrom PA, Axelsson A [1993]. Miniature microphone probe tube measurements in external auditory canal. *J Acoust Soc Am* 93:915. Copyright 1994 American Institute of Physics.)

the same subject for sounds arriving from different locations. These intersubject pressure differences suggest that the variations might be due to differences in the dimensions of the earcanal and pinna; however, there are no studies on such interactions to report at this time. These findings complement earlier findings of Middlebrooks et al (1989), in which location-dependent sound pressure levels were measured with a miniature microphone placed inside the human earcanals. They reported that the sound pressure distribution was highly dependent on frequency and spatial location of the broadband signal. Interactions between frequencies and locations produced location-specific pressure maxima inside the canal for a particular frequency, thus forming characteristic spatial patterns for each frequency.

It is evident that the external ear (pinna and earcanal) augments directionality associated with sounds in free field by adding considerable pressure gain at various frequencies. Accordingly, this direction-dependent filtering of sound by the external ear is ultimately important for monaural spatial perception of sound (Shaw, 1966, 1974a, b; Middlebrooks et al, 1989; Hellstrom and Axelsson, 1993) and for binaural localization.

FACTORS THAT CAN ALTER THE SOUND PRESSURE TRANSFORMATION FROM FREE FIELD TO THE TYMPANIC MEMBRANE

Several factors can affect the sound pressure gain achieved by the external ear. These factors are (1) differences in earcanal dimensions (normal variations and developmental changes); (2) cerumen accumulation, the presence of a foreign body, and integrity of the tympanic membrane; (3) location of the recording microphone in the earcanal, a procedural consideration during sound measurement inside the earcanal for high-frequency measurements, hearing aid prescription, and otoacoustic emissions; (4) the impedance at the plane of the tympanic membrane; and (5) insertion loss due to hearing aid placement.

Differences in Earcanal Dimensions

Techniques to Measure Earcanal Dimensions

Techniques to define the earcanal geometry have been a topic of interest for two reasons: (1) to provide anatomical boundaries and exact dimensions of the external ear and (2) to determine the relationship between sound pressure and the physical geometry/dimensions of the earcanal. The current understanding of human earcanal geometry is quite complicated. Most importantly, the earcanal is not straight but tapered along its length, such that it is wider at the entrance where it flares out into the concha. The inner 10 mm of the canal form a wedge-shaped cavity, with the eardrum forming the one side of the wedge. The earcanal contains twists and turns; it bends upward at the canal-concha junction, and then turns downward near the tympanic membrane. Canal dimensions vary considerably among individuals. According to Shaw (1974 a, b), these dimensions are important when considering the effects on sound pressure distribution in the earcanal.

Early techniques of measuring external ear volume involved filling the earcanal with fluid (Morton and Jones, 1956; Zwislocki, 1971). Recent and more sophisticated procedures range from precise physical measurements of earcanal impressions, to radiological techniques (i.e., computer-assisted tomography [CAT] scanning), and finally to clinical immittance measurements.

Physical Measurements. The physical measurement involves obtaining earcanal impressions, most often from cadaver ears, and measuring the physical dimensions using various techniques (Johansen, 1975; Stinson and Lawton, 1989). Johansen (1975) obtained 10 impressions of the entire earcanal (i.e., cartilaginous and bony parts) and the tympanic membrane from 10 cadavers (6 males and 4 females). These impressions were immersed in a calibrated syringe containing alcohol. The fluid displacement reflected the overall volume of the earcanal, which was 101.4×10^{-2} cm^3 (± 15.4 cm^3), and the mean length of the earcanal measured from the tympanic membrane to the cavam concha was 25.7 mm (± 1.9 mm).

Stinson and Lawton (1989) stated that for an accurate description of sound pressure development inside the earcanal, particularly at high frequencies, the canal dimensions must be accurately defined, rather than accepting the common belief that the earcanal is a uniform tube. The uniform tube representation provided a good approximation of pressure distribution up to 8.0 kHz, but the ability to predict the sound pressure level at higher frequencies required a precise definition of the earcanal geometry. This led to a detailed investigation of the earcanal by Stinson and Lawton (1989), in which they obtained a total of 15 ear impressions from right and left cadaver ears. From these molds, using a specialized mechanical probe system, approximately 1000 points were measured over the entire surface of the mold, starting at the tympanic membrane junction and progressing toward the concha. From these measurements, a three-dimensional representation was generated using a computer program. They pointed out that the earcanal is made up of a series of circular cylinders/slices of varying dimensions connected together.

Johansen (1975) and Stinson and Lawton (1989) undoubtedly provided a better understanding of earcanal dimensions than previous studies. However, a significant limitation with this technique was the difficulty in obtaining deep earcanal impressions in living humans. To overcome this problem, Zemplenyi et al (1985) developed a noninvasive optical method using an operating microscope. The technique involved focusing the microscope on the umbo of the eardrum, marking the location of the viewing arm, and then refocusing the microscope on the lateral aspect of the earmold (near the entrance of the earcanal). The amount of shift in the arm position indicated the length of the earcanal from the concha to the tympanic membrane at the umbo area. This optical method revealed an average canal length of 25 mm for males and 24 mm for females, a finding which was in agreement with the previously published data (Johansen, 1975).

Radiological Studies. Radiological studies have also provided another noninvasive method to measure earcanal volume (Van Willigen, 1976; Eckerdal et al, 1978; Virapongse et al, 1983; Egolf et al, 1993). The CAT scans were used to determine the dimensions of the earcanal. The head (a cadaver's, in most instances) is sequentially scanned at short intervals in horizontal as well as in vertical dimensions. From these scanned images, the earcanal was reconstructed for measurement. Despite several technical challenges, Egolf et al (1993) scanned a cadaver head and compared the radiological findings to physical measurements from earmold impressions. The findings of this study revealed a close match between radiological study and physical measurement, as well as previously published reports using other procedures. Though this is a noninvasive technique, a shortcoming of this procedure is the difficulty in differentiating the soft tissue image from that of bony structures.

Immittance Measurements. A commonly measured function during immittance testing is the volume of the earcanal. The volume measured, in this case, is the column of air between the probe tip and tympanic membrane; therefore, one should not confuse the total earcanal volume obtained by other procedures to that determined by immittance measures. The basic assumption in these measurements is that, when the tympanic membrane is stiffened by pressure, the impedance at the eardrum and the middle ear system is, for practical purposes, considered to be infinite. Consequently, most or all of the sound energy is reflected back. Therefore, the sound pressure developed inside a rigid cavity from a known sound source is directly related to the volume of the cavity. This is an indirect measure based on acoustic immittance. However, controversy exists regarding the use of tympanometric procedures to estimate earcanal volume. For example, when the earcanal is subjected to pressure variations the shape changes, and earcanal pressures as high or low as ±400 da Pa are not enough to drive the middle ear impedance to infinity, and therefore decouple the external ear from the middle ear system.

Rabinowitz (1977) estimated the earcanal volume at ±400 da Pa for a 220-Hz probe tone and suggested that the tympanometric volume estimate (0.76 ml) was 33 percent higher than the actual volume (0.57 ml). Shanks and Lilly (1981) compared the earcanal volume obtained from susceptance tympanograms recorded for two probe frequencies (220 and 660 Hz) and several pressure gradients (between ± 400 da Pa) to the actual measurement by filling alcohol into the free space between the probe tip and the tympanic membrane. They reported that the tympanometric procedures overestimated the actual physical volume. The largest difference was noted for 220 Hz at 200 da Pa (39.0%), and the smallest difference was reported at negative 400 da Pa for both 220 and 660 Hz. The 660-Hz probe tone more closely reflected the actual volume (10% error) than the 220-Hz tone (24% error). These differences were attributed to the variation in the reactance of the middle ear system at these two frequencies. Shanks and Lilly (1981) suggested that a probe frequency closer to the middle ear resonance (800–1200 Hz) would estimate the volume more accurately than other frequencies. Therefore, if one is interested in measuring the earcanal volume, it is advisable to use probe frequencies closer to the middle-ear resonant frequency, thereby reducing the variability introduced by the middle ear effects.

In quantifying the dimensions of the earcanal, particularly its volume, our sophistication has increased from considering the earcanal as just a simple cavity or as a cylindrical tube to a serial connection of circular cylinders, each representing one thin, cross-sectional slice of the earcanal. The published findings on earcanal geometry from several investigators are summarized in Table 1.

Developmental Variations

There are substantial differences between adults and infants in head size, pinna size, and earcanal dimensions. Developmental studies have indicated that the shape and size of the earcanal changes from the postnatal period to 7 to 9 years of age (Ballachanda, 1995). Nevertheless, infants and children are being fitted with hearing aids at early ages based on electroacoustic measurements made on KEMAR or the typical adult head. Perhaps this is because there are considerably fewer studies on sound pressure measurements in the earcanals of young children and infants compared to adults.

Despite the difficulties associated with recording sound pressure inside the earcanal of children and infants, a few studies have measured earcanal resonance as a function of age (Kruger, 1987; Bentler, 1989; Dempster and Mackenzie, 1990; Keefe et al, 1994). The general agreement from these studies is that, at birth, the earcanal resonance is usually around 6.0 kHz (Kruger, 1987) and decreases with increasing age. By the age of 2 years, the resonance is around 2.7 kHz, which corresponds to adult values (Kruger, 1987; Bentler, 1989, 1991; Keefe et al, 1994). The shift from higher to lower frequency in the resonance peak with increasing age was attributed to the change in the earcanal dimensions. The exact age at which the adult resonance values are reached has been a topic of discussion, though most studies suggest 2 years as the cutoff point. However, Dempster and Mackenzie (1990) noted changes in resonant frequencies up to 7 years in some children. The reason for this discrepancy was attributed to differences in earcanal size in their subjects even though the children were the same chronological age.

In another study, Keefe et al (1994) measured the outer ear transfer function in a diffuse

Table 1 Summary of Earcanal Length and Dimensions Recorded from Various Techniques

Investigators	*Parameters and Type of Measurement*	*Dimensions*
Johansen (1975)	Length of the earcanal—physical measurement	25.7 mm (±1.9 mm)
	Ear canal volume	1014.0 ± 15.4 mm³
Djupesland and Zwislocki (1972)	Length of the earcanal—physical measurement	Male 23.8 mm Female 22.0 mm Combined 23.0 mm
Zemplenyi et al (1985)	Length of the earcanal—optical method	Male 25.0 mm Female 24.0 mm
Chan and Giesler (1990)	Length of the earcanal	
	Optical method	Male 23.4(±2.1) mm Female 19.7 (±0.9) mm
	Acoustic method	Male 23.4 (±1.9) mm Female 20.9 (±0.9) mm
Sàlvenilli et al (1991)	Length of the earcanal	Male 25.2 (±2.6) mm Female 22.4 (±2.3) mm Total 3.5 (±2.5) mm
	Longest diameter	Male 9.7 (±1.5) mm Female 8.5 (±0.7) mm Total 9.4 (±1.5) mm
	Shortest diameter	Male 5.1 (±0.7) mm Female 4.4 (±0.3) mm Total 4.8 (±0.5) mm
Egolf et al (1993)	Earcanal volume	
	CAT scan images	1211.51 mm³
	Mold impressions	1290.49 mm³

sound field for human infants aged 1, 6, 12, and 24 months. They noted two peaks in the 2.0- to 6.0-kHz range, reflecting the combined resonance of the earcanal and concha. The earcanal resonance decreased from 4.4 kHz at 1 month to 2.9 kHz at 24 months; correspondingly, the concha resonance also decreased from 5.5 kHz at 1 month to 4.5 kHz at 24 months. They proposed a simple two-cylinder model to predict the sound transformation function in children. These findings suggest that the earcanal resonance decreases from the postnatal stage to 2 years of life. Again, an important factor responsible for the decrement in the resonant frequency appears to be the size of the external ear (concha and earcanal).

Even normal developmental variations in the shape and size of the outer ear can significantly alter the sound pressure build-up in the earcanal. For example, the spectrum of a standard a click delivered to an adult earcanal will be different from the spectrum of that same click in the earcanal of a child or an infant. Johnson and Nelson (1991) reported that acoustic characteristics of the clicks routinely used for ABR testing in infants and adults were spectrally different when measured inside the earcanal. The mean resonance frequency recorded for clicks in infants was considerably higher (2339.77 Hz) than that recorded in adults (1618.75 Hz). In addition, there was greater variability in the resonance peaks in infants (669.3 Hz) than in adults (319.0 Hz). According to Rubel et al (1984), newborn and infant cochleae may not be responsive to higher frequencies. Therefore, it is possible that clicks in the infant's earcanal may not be stimulating the frequency region capable of exciting a maximal response. The result may be reduced excitation of the critical cochlear region, poor responses, and difficulty in interpreting the test results. Therefore, the importance of individual measurements to determine stimulus actually reaching the tympanic membrane must be emphasized in clinical testing. Chertoff and Chen (1996) reported in-situ calibration procedure as a possible solution to the individual differences in earcanal sound pressure.

Effects of Cerumen, Foreign Bodies, and Integrity of Tympanic Membrane

An earcanal occlusion (either partial or complete) is assumed to change the volume of the earcanal. It is common in audiology clinics to observe earcanals impacted or occluded with cerumen. The degree to which these impactions cause alterations in the resonance properties of the earcanal remains unanswered. Chandler (1964) examined the effects of earcanal occlusion by measuring the relation between the amount of blockage to the amount of threshold shift across audiometric frequencies. Based on his findings, he concluded that earcanal blockage resulted in threshold shift; a complete occlusion produced an average threshold shift of 30 dB at frequencies above 2.0 kHz. Recently, Gerling et al (1992, 1997) reported that varying amounts of cerumen impaction can produce significant differences in real-ear unaided response (REUR) between and within subjects. These REUR were determined by comparing pre- vs postcerumen extraction measurements. In general, these transient results showed an overall decrease in amplitude in primary and secondary peaks and shift of both peaks toward higher frequencies. It is imperative that such transient changes can have considerable effect on the outer ear frequency response and consequently alter the aid fitting parameters.

Tympanic membrane perforations can also have dramatic effects on the resonant frequencies of the earcanal. Moryl et al (1992) reported that the size and shape of the earcanal resonant peaks varied considerably depending on the size of tympanic membrane perforation. Smaller tympanic membrane perforations produced resonant peaks similar to those of nonperforated tympanic membranes. Ears having large tympanic membrane perforations exhibited bimodal peaks separated by large troughs that were often above or below the normally expected range of 2.7 kHz. Moryl et al (1992) also showed that resonant peaks in ears with large tympanic membrane perforations became more normal in appearance after surgical closure of the perforation. They suggested that their findings could have important implications for selecting and fitting hearing aids to ears with perforations. Thus, audiologists and others involved in auditory function measurements must be alert to changes in earcanal volume due to the presence of cerumen, foreign objects, or tympanic membrane perforations.

Location of the Recording Microphone in the Canal

An important procedural consideration when measuring the sound pressure in the earcanal is the placement of the probe tube/microphone in the canal. The magnitude of the sound pressure measured inside the earcanal is highly dependent on the exact location of the point of measurement, due to the presence of standing waves and variations in the shape of the canal. Consequently, location-dependent variations can produce substantial differences in the sound pressure recorded inside the earcanal, especially for frequencies above 3.0 kHz.

The reasons for the pressure variation or the presence of standing waves in the earcanal are detailed as follows. When a sound impinges on the tympanic membrane, some of the energy is dissipated, some is reflected back, and most of the energy is transmitted through the tympanic membrane into the middle ear. The reflection of energy is due to impedance differences between the tympanic membrane (Z tympanic membrane) and the transmission line (Z earcanal). The interaction between the reflected and incident waves results in standing waves with pressure maxima and minima at different points along the earcanal (Stinson et al, 1982; Gilman and Dirks, 1986; Dirks and Kincaid, 1987; Stinson and Khanna, 1994). A schematic representation of the standing wave patterns in a rigid-walled cylindrical tube is illustrated in Figure 4 (Gilman and Dirks, 1986). Plotted on the abscissa is the location of the probe microphone with respect to the tympanic membrane, while the ordinate shows the difference in sound pressure measured (i.e., the amount of sound pressure underestimated by the probe microphone to the level present at the tympanic membrane). These pressure minima and maxima are at different locations along the length of the canal, dependent on frequency; the first minima is usually observed at a distance equal to the quarter-wave length ($\lambda/4$) of the frequency of the stimulus (e.g., a probe microphone placed at 1.0 cm from the tympanic membrane can change the sound pressure values by as much as about 10 dB for an 8.0-kHz tone compared to a placement closer to the tympanic membrane). For frequencies below 3.0 kHz, the pressure maxima or minima are negligible or insignificant because the minima of the standing waves fall outside the length of the earcanal; however, at higher frequencies, the number of pressure minima and maxima increases monotonically with the frequency.

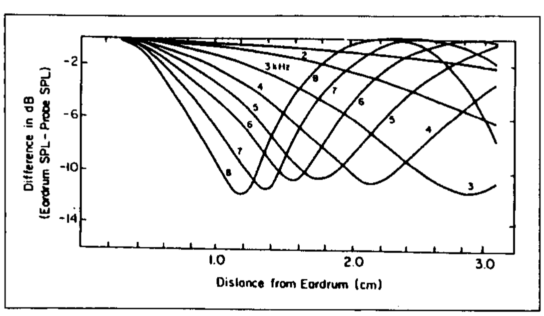

Figure 4 Standing waves for frequencies 1.0 to 8.0 kHz. The negative values on the ordinate refer to the pressure difference in dB between eardrum and probe measured sound levels at different locations along the earcanal. (Reproduced with permission: Gilman S, Dirks DD. [1986]. Acoustics of ear-canal measurement of eardrum SPL in simulators. *J Acoust Soc Am* 80:786. Copyright 1986 American Institute of Physics.)

Impedance at the Plane of the Tympanic Membrane

In addition to the location of the microphone, the impedance of the tympanic membrane and the middle ear have significant effects on the specific location of the pressure maxima and minima in the earcanal. Gilman and Dirks (1986) reported that high and low impedance systems tend to produce minima at different locations compared to a normal system. High impedance systems appear to produce minima closer to the tympanic membrane, whereas low impedance systems produce minima at locations farther from the tympanic membrane.

In clinical practice, the probe microphone should be placed close to the tympanic membrane; a distance of 5 mm from the tympanic membrane can achieve the necessary accuracy of measurement even for high frequencies. When performing repeated measurements, the probe/microphone must be placed at the same location. Additionally, any middle ear problems should be noted during the earcanal measurements; if possible, the results should be repeated after any abnormal middle ear conditions have been resolved.

Insertion Loss due to Hearing Aid

Hearing aid placement in the canal can also alter the resonance characteristics of the earcanal. The loss of resonance due to placing a hearing aid in the earcanal is known as "insertion loss." The amount of insertion loss depends on the type of hearing aid; deeper earmolds result in a greater loss.

SUMMARY

This paper has reviewed the acoustic properties of the external ear. The external ear plays a major role in sound pressure transfer from free field to the tympanic membrane; it acts as a filter to reduce low frequencies and as a resonator to enhance mid to high frequencies. The amount of pressure gain in the mid to high frequencies is directly related to the anatomical dimensions of the external ear. Any changes in the dimension of these structures can alter the characteristics of the sound reaching the tympanic membrane from the free field. Therefore, in clinical practice, knowledge of the external ear acoustics is important for two reasons: first, to understand how the sound delivery system (i.e., the earphone and hearing aids) and the earcanal can alter the spectral of the signal reaching the tympanic membrane; second, to know where to place microphones inside the earcanal during otoacoustic emission testing, calibrations purposes, and real-ear hearing aid measurement.

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