Audio Engineering Society

Convention Paper

Presented at the 130th Convention
2011 May 13–16 London, UK

Sound Reproduction within a Closed Ear Canal: Acoustical and Physiological Effects

Samuel P. Gido[1,2], Robert B. Schulein[1], and Stephen D. Ambrose[1,*]

[1] Asius Technologies LLC, 1257 Whitehall Drive, Longmont, CO 80504

[2] Polymer Science & Engineering Department, University of Massachusetts, Amherst, MA 01003

[*] to whom correspondence should be addressed: Stephen.Ambrose@AsiusTechnologies.com

ABSTRACT

When a sound producing device such as insert earphones or a hearing aid is sealed in the ear canal, the fact that only a tiny segment of the sound wave can exist in this small volume at any given instant, produces an oscillation of the static pressure in the ear canal. This effect can greatly boosts the SPL in the ear canal, especially at low frequencies, a phenomena which we call Trapped Volume Insertion Gain (TVIG). In this study the TVIG has been found by numerical modeling as well as direct measurements using a Zwislocki coupler and the ear of a human subject, to be as much as 50dB greater than sound pressures typically generated while listening to sounds in an open environment. Even at moderate listening volumes, the TVIG can increase the low frequency SPL in the ear canal to levels where they produce excursions of the tympanic membrane that are 100 to 1000 times greater than in normal open-ear hearing. Additionally, the high SPL at low frequencies in the trapped volume of the ear canal, can easily exceed the threshold necessary to trigger the Stapedius reflex, a stiffing response of the middle ear, which reduces its sensitivity, and may lead to audio fatigue. The addition of a compliant membrane covered vent in the sound tube of an insert ear tip was found to reduce the TVIG by up to 20 dB, such that the Stapedius reflex would likely not be triggered.

1. INTRODUCTION

From the 1960's to the present, co-author Stephen D. Ambrose has been investigating and developing improved technology for coupling sound into the human ear.[1] This effort began with his introduction and refinement of the first in-ear monitors (IEM), by the second half of the 1970's. These devices, including wireless links and ambient monitoring, were adopted and used extensively by a wide range of top studio and touring musicians.[2] Aside from the user benefits provided by IEM devices over traditional stage monitors, the fact that he was both and engineer and a vocal performer gave him a unique grasp of the full range of drawbacks associated with sealing a speaker in the ear. Among these were excessive SPL, audio fatigue, the occlusion effect, and other serious issues with pitch perception, frequency response, and dynamic range, which do not exist in open-ear or natural acoustics. Development and experimental efforts undertaken throughout the 1970's and 1980's to alleviate these issues, culminated in a previously issued patent.[3], providing partial solutions. The present paper provides a scientific explanation of Ambrose's previous observations about sealing sound producing devices in the ear, and discusses his most recent technology to mitigate these effects.

Audio speakers, when inserted and sealed in the human ear, can produce large oscillations in pressure within the ear canal, even when the speakers are operated at what would normally be considered modest input power. These pressures differ from acoustical sound pressures as they normally exist in open air or in larger confined volumes. The tiny confined volume of the ear canal, which is much smaller than most acoustical wavelengths, causes the sound pressure in the ear canal to behave as if it is a static pressure, like the pressure confined in an inflated balloon or the static pressure employed in Tympanometry[4-6]. But, paradoxically, this static pressure is also changing very rapidly, i.e. it is oscillating at acoustical frequencies. The presence of oscillating static pressure, when the ear canal is sealed with a listening device, can produces a dramatic increase in sound pressure levels (SPL), which we call the *Trapped Volume Insertion Gain (TVIG).* Even when the input power to the listening device, sealed in the ear, is quite modest, the TVIG effect can subject the listener to SPL levels that exceed the threshold for the *Stapedius Reflex*[7-14]. This reflex is a natural mechanism by which the contraction of the stapedius muscle in the ear reduces the ear's sensitivity in order to protect itself from being damaged by loud noises and to widen its dynamic range to tolerate higher sound pressure levels. This reduction in hearing sensitivity has the potential to diminish the dynamic quality of audio perception through insert headphones or hearing aids. The oscillating static pressure trapped in the ear canal is also responsible for gross over-excursions of the tympanic membrane (ear drum) that can be 100, or 1000, or more, times greater than the normal oscillations of the ear drum associated with sound transmitted through the open air.

It seems particularly counter productive to have devices intended to provide high fidelity audio (insert headphones, ear buds, etc.), or aid to the hearing impaired (hearing aids) that simultaneously reduce hearing sensitivity by triggering the stapedius reflex. It is possible that trapped volume insertion gain, which is operating continuously as long as the device is sealed in the ear canal, causes the Stapedius Reflex to be triggered again and again. This is not a normal condition for the stapedius muscle, and it significantly contributes to and may even be the main cause of listener fatigue, in which peoples' ears begin to physically ache or hurt after prolonged use of in-ear devices.

Here we also discuss new approaches to mitigate the negative impacts of sealing a listening device in the ear. These approaches essentially allow the trapped volume in the ear canal to behave acoustically as if it is not trapped, or at least less confined than it actually is. This at least partially transforms the sound energy in the trapped volume in the ear canal from an oscillating static pressure back into a normal acoustic wave, which is lower in amplitude and less punishing in its effects on the ear drum, the stapedius muscle, and the ear in general.

2. SPEAKER SEALED IN THE EAR CANAL

When a speaker is sealed in the ear canal, creating a small trapped volume of air, the familiar physics of sound generation and sound propagation in open air is altered dramatically. If the length of this trapped volume in the ear canal is taken to be about 1 cm or less (values vary by individuals and with the type of device and depth of insertion in the ear), Figure 1 shows the length of the trapped volume as a fraction of the wavelength of sound across the frequency range. Especially for low frequencies, but extending up into the mid-range, the trapped volume in the ear canal is only a small fraction of the wavelength of the sound.

Within this small trapped volume, only a tiny snippet at a time of an oscillating pressure profile (what would be a normal sound wave in open air) can exist. Especially for lows and mid-range frequencies, the pressure across this small trapped volume is very nearly constant because the ear canal is only sampling a small section of the "wave" at a given instant. As a result of the fact that pressure maxima can no longer coexist in time with pressure minima (as they do in open air sound waves) the average static air pressure of the system is no longer constrained to remain constant (as it is for sound wave

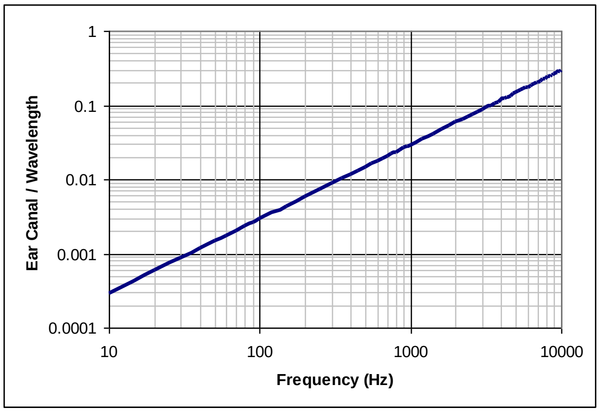


Figure 1: Size of the Trapped Volume (ear canal) relative to the Wavelength of Sound

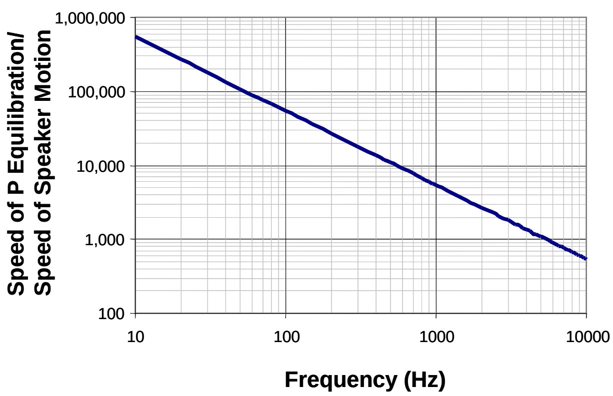


Figure 2: Speed of Pressure Equilibration in the Ear Canal Relative to the Speed of Speaker Motion

propagation in open air). In fact, the overall pressure in the trapped volume of the ear canal can oscillate dramatically, and this results in excursions of the tympanic membrane that are orders of magnitude larger than in normal, open-ear listening.

We refer to this pressure, caused by a sealed speaker in the ear canal, as a *static pressure*. One reason for doing so is that this pressure bears some similarity in its effect on the tympanic membrane to the static pressure applied in the diagnostic technique of tympanometry.[4-6] In tympanometry, the ear canal is sealed with an insert earphone and air is pumped in and out of the sealed volume to both increase and reduce the pressure in the sealed volume relative to atmospheric pressure (and the pressure in the middle ear). This pressurization of the ear canal in tympanometry is referred to as *static pressure*, to distinguish it from the SPL employed in the technique, which is oscillating at acoustical frequencies, and is generally of much lower magnitude. As discussed below, the static pressure induced when a headset or hearing aid with a speaker is sealed in the ear canal, has a dual character. It is simultaneously a static pressure, like the pressure produced by pumping air into the ear canal in tympanometry, and an oscillating sound pressure which can be measured as SPL.

The static pressure in the ear canal is the pressure that results from a change in the volume (a compression or rarefaction) of a fixed amount of air trapped in the ear canal. This static pressure may, at any instant, be greater than, equal to, or less than the barometric pressure outside the ear. The static pressure may be changing (oscillating) rapidly, and thus the use of the term *static* may seem strange. However, the term *static* refers to the fact that this pressure is not a transient oscillation in pressure (i.e. a sound wave in open air) but rather is a thermodynamic, equilibrium property of the air mass associated with its volume. If the volume of this fixed mass of air is held constant (i.e. the speaker diaphragm is frozen at any point of its motion) then the static pressure will remain constant. If the volume of this air mass is changing or oscillating with the speaker motion then this thermodynamic, equilibrium property (static pressure) will also be changing or oscillating. This is true of the static pressure oscillations produced by a speaker sealed in the ear canal, provided that the rate at which pressure equilibrium is established at every incremental position of the moving speaker diaphragm is much faster than the motion of the diaphragm. The static pressure equilibrates via molecular motions that propagate across the 1 cm length of the trapped volume at the speed of sound. Figure 2 plots the ratio of the speed of pressure equilibration vs. the peak speed of speaker motion across the frequency range. Clearly, the equilibration of pressure is much faster (thousands to hundreds of thousands of times faster) than the change in pressure resulting from speaker motion, and thus the pressure is at quasi-equilibrium, at any given instant, with respect to the influence of the moving speaker diaphragm, especially at lower frequencies.

2.1. Acoustic Analysis

Beranek, analyzed the case of a rigid piston oscillating in one end of a rigid tube, which is closed on the opposite end.[15] His analysis focuses mainly on tubes, which are long enough to set up standing wave patterns with various locations of increased and decreased pressure along the tube. However, Beranek's Equations 2.47 and 2.48 (reproduced below), which give the pressure profiles along the length of the tube, are equally applicable to very short tubes, although Beranek, himself, did not explore the implications in his book. Clearly, insert headphones that seal in the ear canal were not as prevalent around 1950, when Beranek did this work.

$$p(x,t) = -j\rho_0 c\sqrt{2}\, u_0 e^{j\omega t}\frac{\cos k(l-x)}{\sin kl} \qquad (2.47)$$

$$p = -j\rho_0 c u_0 \frac{\cos k(l-x)}{\sin kl} \qquad (2.48)$$

In these equations u is the piston speed, ρ is the density of air, c is the speed of sound, l is the tube length, x is the coordinate along the tube from zero at the piston's zero displacement position up to l. k is $2\pi/\lambda$, where λ is the wavelength. The "o" subscripts on the u and ρ values indicate the use of root-mean-square *(rms)* values and the equations then yield *rms* pressures. The equations, however, apply equally well to peak valves (drop the subscripts) and then give peak pressure (i.e. amplitude of the pressure oscillations). The term j is the imaginary number, also frequently know as i. Disregarding the i, which has to do with getting the correct phase of the time oscillation, Equation 2.48 gives the amplitude of the resulting pressure wave in the tube as a function of distance x, along the tube.

Figure 3 shows the pressure profiles along a 1 cm long tube, approximating the length of the sealed, trapped volume in the ear canal calculated from Beranek's equations. The pressures plotted are the ratios of the amplitude (maximum value) of the pressures in the sealed tube divided by the pressure amplitude of the sound waves that the same piston motion would produce in open air (the sound radiated by a diaphragm of similar diameter radiating into free space). The pressure in the small closed tube is significantly higher than in open air, except at high frequencies. This graph shows that at an instant in time that the pressure is very uniform along the 1 cm length of the tube.

Of course the pressure is also oscillating in time. Figure 3 shows the profile at the time when pressure is maximum. The pressure profile is equally flat with distance along the tube, but at other pressure levels, at other points in the time oscillation. As the pressure in the tube changes, these changes must propagate across the tube from the moving piston at the speed of sound. The small length of the tube, relative to the wavelength

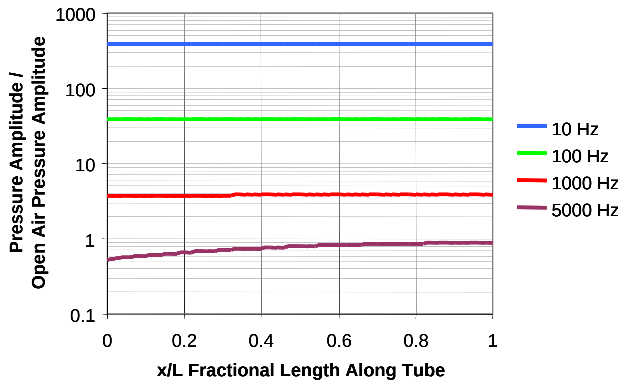


Figure 3: Pressure Profiles Along a 1cm Long, Rigid Tube with a Vibrating Piston in the End

of the oscillations, however, means that the pressure profile across the tube equilibrates at each time much faster than the overall pressure level is changing with time as a result of the piston oscillations. Thus the pressure across the tube can be considered constant at any instant.

The constant pressure amplitudes across the 1cm sealed tube length, given in Figure 3 are quite similar to the pressures in the trapped volume of the ear canal calculated for a much more involved model taking into account the compliances and motions of the structures of the middle ear (tympanic membrane, etc.). These more realistic values are plotted in Figure 7, below. The values in Figure 3 are a higher than those in Figure 7, because the Beranek model is for a completely rigid sealed tube, with no way to mitigate the pressure increase through the motion of its surfaces.

Beranek's model of acoustical waves in a closed, rigid cylinder shows that the pressure waves produced by the oscillating piston, at one end, interfere with waves reflected off the opposite end of the tube. The resultant pressure profile in the tube is the standing wave pattern associated with the interference of this forward and reflected wave. The pressure profiles plotted in Figure 3, resulting from this model, show that in the case where the tube is a small fraction of the wavelength of the sound, that the standing pressure waves yield a flat pressure profile across the tube. There are no nodes and antinodes of high and low pressure of the type Beranek plots[15] in his Figure 2.6, if the tube length is very short. The result of the interference of forward and reverse traveling waves in the closed tube also leads to a 90 degree phase shift in the pressure wave relative to the motion of the driving piston. In Beranek's analysis this phase shift is seen to be a result of the interference of a forward and a reverse traveling acoustical wave.

The fact that the pressure profile in the short tube is quasi-static and thus may be analyzed as an oscillating static pressure, rather than as an acoustic wave, can be proved by transforming Beranek's equation 2.48, in the limit of small l/λ into an expression, which is the mathematical definition of the pressure vs. volume behavior of a confined gas volume under static pressure. We start with a simplified version of Beranek's Equation 2.48 for the peak pressure value (pressure amplitude) as a function of distance, x, along the tube.

$$P = \rho\, c\, u \cos(k(l - x)) / \sin(kl) \qquad (1)$$

We recognize that when l/λ is very small that we can employ the normal approximations to the values of the cosine and sine functions when their arguments are small: The cosine with a very small argument is very close to one, and the sine with a very small argument is well approximated by the argument itself. The validity of these approximations is the direct mathematical cause of the flatness of the pressure profiles in Figure 3 for frequencies up to at least 1000 Hz. With these approximations the expression for the pressure becomes:

$$P = \rho\, c\, u / (kl) \qquad (2)$$

The maximum speed of the piston, u, is equal to $\omega\delta$, where δ is the maximum displacement of the piston. Substituting this into Equation 2, along with the value of k in terms of wavelength, and utilizing the relationship $c = \omega\lambda/(2\pi)$, one obtains:

$$P = \rho\, c^2\, (\delta / l) \qquad (3)$$

The total volume of the sealed tube, V, is equal to Sl, where S is the cross-sectional area of the tube. The change in volume of the tube, ΔV, is equal to $S\delta$. And, therefore, (δ / l) is equal to $(\Delta V/V)$, the factor of S cancelling out of the numerator and denominator. Additionally, the fundamental definition of the speed of sound in terms of the mass and compliance of the medium in which is traveling is: $c^2 = B/\rho$, where B is the bulk modulus (resistance to change in volume)[16]. Therefore:

$$P = B\, (\Delta V/V) \qquad (4)$$

Equation 4 is the very definition of the pressure vs. volume change properties of a gas undergoing a static pressure compression or rarefaction. This has been derived, starting from an acoustical equation and imposing the limit of small tube length relative to wavelength. This proves that in this limit, we can safely analyze the case of a speaker sealed in the ear canal in terms of its static pressure effects.

A further insight links the reflection of the sound wave at the rigid back wall of the sealed tube, in Beranek's acoustical derivation, with the concept of static pressure. When the piston in the tube moves forward and compresses the gas, the rigid boundary of opposite end of the tube can either be thought of as a wall which limits the volume change of the tube at its far end, and thus enables the piston to produce a ΔV, or it can be considered a hard wall boundary condition, which reflects an acoustical wave and sends a reverse wave back down the tube. The result of either analysis is exactly the same for a small tube length. Therefore, a speaker sealed in ear canal operates like pneumatic piston, producing time oscillations in overall or static pressure (analogous to barometric pressure in open air) in the trapped volume of the ear canal. These static pressure oscillations certainly do move the tympanic membrane.

When the speaker is sealed in the ear canal, the peak oscillating static pressure is determined not by the maximum speaker diaphragm speed (as in the case of open air acoustic waves) but by the maximum speaker excursion, δ in Equation 3. This is, in fact, exactly the opposite of the open air operation of the speaker. However, this is also obviously true for the sealed volume case. When a speaker diaphragm moves forward into the trapped volume of the ear canal, it reduces that volume by the product of the speaker area and the distance the speaker is moving. The speed with which this occurs is not important to the static pressure achieved in the trapped volume. But the extent of speaker motion determines the amount of volume reduction, which is directly related to the corresponding static pressure increase by the compressibility of the air (Equation 4). The fact that the maximum static pressure occurs at the maximum speaker displacement, rather than the maximum speaker velocity, is another way of understanding the 90 degree phase shift of the oscillating static pressures, relative to normal, open air sound. The confinement in a small trapped volume can lead to static pressures in the ear canal which are much larger (up to hundreds of times larger) than the sound pressures present in open air sound waves. This can trigger the stapedius reflex, thereby reducing the sensitivity of human hearing, and results in strong motions of the tympanic membrane, which are also much larger than those in normal open ear hearing.

An oscillating speaker sealed in the ear canal produces large amplitude, static pressure waves associated with the maximum displacement of speaker motion. However, the acoustical science view of what is happening, as embodied in Beranek's analysis above, indicates that acoustical pressure disturbances are simultaneously being generated and are associated with the maximum speed of the speaker diaphragm. It is the interaction of the forward and reverse traveling acoustical waves that generates the static pressure in the small confined volume, and makes the overall phenomenon appear to be related to speaker displacement and to be 90 degrees out of phase with the speaker velocity. Thus the phenomena occurring in a small trapped volume, such as the ear canal, has a dual character. The oscillating pressure effects in the sealed ear canal are both acoustical waves and static pressure oscillations at the same time. Which of these two aspects of the phenomena is dominant, depends on the conditions. For instance, smaller confined volumes and lower frequencies (longer wavelengths) produce an oscillating-static-pressure-like behavior, while larger trapped volumes and higher frequencies yield an acoustical-wave-like behavior.

It would be convenient to define a criteria or parameter that governs whether or not sound waves in a particular medium, at a particular frequency, can be interpreted as an oscillating static pressure in a confined volume of a specific size. The most rigorous test of static pressure character is that the standing wave pressure profile calculated from Beranek's Equantion 2.48 (Eqn. 1) is nearly constant at every location, x, along the length of the trapped volume. This profile as calculated from the Equations will never be mathematically, exactly constant due to the nature of the mathematics employed. However, the profile can be considered functionally constant, when the calculated variations in the pressure profile are smaller than what can be measured experimentally, or alternatively are smaller than the random and transient, natural thermal fluctuations in the pressure that are always present in any system. This is equivalent to the condition that kl is very small, which is in turn equivalent to the condition that l/λ is very small. The criterion is expressed as the ratio of the length scale associated with pressure equilibration, l, to the length scale associated with pressure variation, λ, due to sound. Exactly the same criterion can also be expressed as the ratio of the time scale of pressure equilibration in the trapped volume to the time of sound wave pressure variation, or ($l\nu/c$), where ν is the frequency.

2.2. Modeling a Speaker with a Trapped Ear Canal Volume

2.2.1. Static Pressure Model

A model, shown schematically in Figure 4, was analyzed to get an indication of the responses and the trends associated with the static pressure effects of sealing a speaker in the ear canal. This model consists of a tube of length and diameter intended to approximate the dimensions of the trapped volume in the ear canal. It is taken to be 7 mm in diameter and the length, L (the same parameter as l used in Beranek[15]), can be varied to simulate different speaker insertion depths resulting in different trapped volume sizes. Tube lengths of 1.0 and 0.5 cm were used for illustrative calculations.

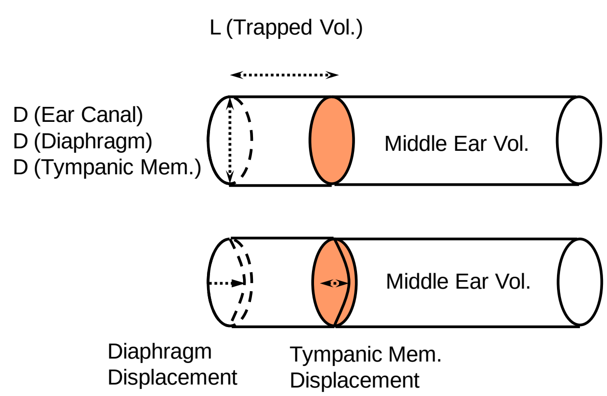


Figure 4: Schematic of Model for Trapped Volume in the Ear Canal

One end of the tube is covered by a flexible membrane, which has an initial hemispherical dome shape, 2 mm higher in the middle than around its edges. This represents a speaker geometry, and it can be displaced along the direction of the tube axis to simulate the motion of the speaker diaphragm. During displacement, the speaker remains attached to the tube around its edges, and this attachment does not move. The speaker displacements quoted in this study refer to the displacements of the center of the dome speaker. During such displacements the overall speaker shape is adjusted to remain hemispherical while remaining attached at its edges to the tube.

The other end of the tube is covered by a membrane with an elastic modulus equal to an average value measured for human tympanic membranes: E (Young's Modulus) = 3 N/m^2.[17-19]. The tympanic membrane is not flat, but rather an asymmetric, shallow, conical shape, although this aspect of the real tympanic membrane shape has only a minor effect on the static pressure calculations presented here. The tympanic membrane is modeled with a thickness of 0.8 mm, an average value for humans. Both the speaker diaphragm and the tympanic membrane are assumed to have the same diameter as the tube. The pressure inside the sealed tube (ear canal) is initially atmospheric pressure. On the other side of the tympanic membrane is another volume, which simulates that of the middle ear. This middle ear volume is also initially at atmospheric pressure, and it has a volume of 1.5 cm^3, an average value for the human population.[20] The computational model, illustrated in Figure 4, is very similar to an actual physical model of the ear canal used in recently reported experiments on the acoustics of insert headphones.[21]

When the speaker diaphragm is displaced toward the trapped volume, decreasing the volume, the model system distributes the effect of this disturbance between the pressurization of air in the sealed volume of the ear canal and the displacement of the tympanic membrane. The displacement of the tympanic membrane also displaces and pressurizes air in the middle ear cavity. The pressurization of the air in the ear canal and in the middle ear volume is resisted by the compressibility modulus of the air, which is derived from the Ideal Gas Law. The Ideal Gas Law is an excellent representation of the behavior of air at body temperature and near atmospheric pressure, as the compressibility factor (Z) is essentially equal to one [22]. The stretching of the tympanic membrane, due to the pressure differential between the sealed ear canal volume and the middle ear volume, is resisted by the stretching modulus of the tympanic membrane, and is modeled as in Reference [23]. The actual vibrational modes and extensional geometries of the tympanic membrane may be quite complex.[24,25] They are simpler and more similar to the simple hemispherical deformation model used here, at lower frequencies.

Wada, Kobayashi and co-workers[18,19] have done extensive measurements and mechanical modeling of different components of the human middle ear. They show that excursions of the tympanic membrane involve deformation not just of the tympanic membrane itself, but also of the connection between the tympanic membrane and the ear canal, and of the ossicular chain, which connects the tympanic membrane to the cochlea. They have determined mechanical moduli associated with these other aspects of tympanic membrane deformation, which are included in the model described in this section.

Modeling of the static pressure effects with a speaker sealed in the ear depends only on the net change in trapped volume associated with the combined motions of the speaker diaphragm and the tympanic membrane. These changes depend on speaker and tympanic membrane geometry, but not on the ear canal geometry, since the morphology of the ear canal along the trapped volume remains the same as the volume changes. The other piece of information required to do the model calculation is the resistance to deformation of the tympanic membrane, including all the modes of deformation and the resistance to deformation of structures attached to the tympanic membrane that must move with it.

Wada and Kobayashi [18,19] give an equivalent (spring-like) modulus for the attachment of the tympanic membrane (k_w = 4000 N/m^2) and for the ossicular chain connection between the tympanic membrane and the cochlea (k_s = 700 N/m^2). The model is evaluated, for a given speaker displacement, by setting the pressure difference between the trapped volume in the ear canal and the pressure in the middle ear volume equal to the pressure across the deformed tympanic membrane. The deformation of the tympanic membrane is modeled to including the biaxial deformation of the tympanic membrane itself, the deformation of the attachment of the tympanic membrane and the motion of the attached ossicular chain.

Calculations based on this model were performed for a range of speaker displacements from 1 to 400 microns, and for frequencies ranging from 10 Hz to 1000 Hz. The resulting tympanic membrane displacements and pressure increases in the closed, ear canal volume were calculated. The pressure increase in the closed, ear canal volume was compared to the sound pressure in open air that the same speaker motion would generate. In order to perform the open air calculation, the speaker displacement and frequency were used to calculate the maximum diaphragm velocity assuming sinusoidal diaphragm displacement vs. time. Under these conditions the maximum diaphragm velocity is $\omega\delta$, where ω is the angular frequency equal to 2π time the frequency, and δ is the amplitude of speaker displacement.

Figure 5, shows total tympanic membrane displacement vs. speaker displacement. The tympanic membrane displacement is in the multiple micron range and goes up with increasing speaker displacement. Figure 6 shows the same tympanic membrane displacement vs. speaker displacement data as Figure 5 except that the tympanic membrane displacement is shown as a percentage relative to the driving speaker displacement. Note that there is no frequency dependence of the tympanic membrane displacement, in these results, since the displacement depends on static pressure, which is related to speaker displacement, not to speaker velocity. This will be shown, below to be a good estimate for relatively low frequencies, specifically those below about 100 Hz. Speaker displacements in the micron range produce static-pressure-driven, tympanic membrane excursions that are also in the micron range, these are 100 to 1000 time the normal tympanic membrane excursion amplitudes, which are tens to hundreds of nanometers.[25] The tympanic membrane displacements are significantly larger for the smaller trapped volume (L = 0.5 cm) than for the larger trapped volume (L = 1.0 cm). This is because the same speaker displacement, giving the same volume change, ΔV, relative to a smaller trapped volume, $\Delta V/V$, produces a greater fractional (or percentage) change in volume, $\Delta V/V$, and this produces a greater pressure increase via Equation 4.

Figure 6 shows that the percentage of speaker displacement transferred to the tympanic membrane is fairly uniform with speaker displacement and has a value of about 40 to 45% for the smaller trapped volume and 25 to 27% for the larger tapped volume. These are very large transfers of speaker motion to the tympanic membrane. Equivalent speaker motions in open air, even very pronounced motions, peak or rms sound pressures that are only a small fraction of atmospheric pressure. The peak and rms values of the oscillating static pressure in the trapped volume of a sealed ear canal, are higher at all speaker displacements than the open air values.

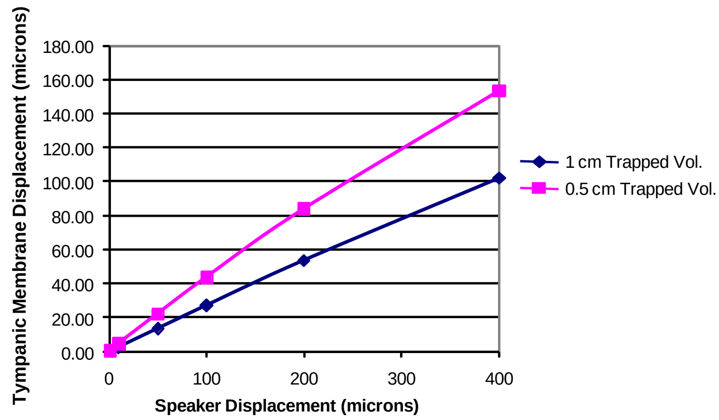


Figure 5: Tympanic Membrane Displacement as a Function of Speaker Displacement

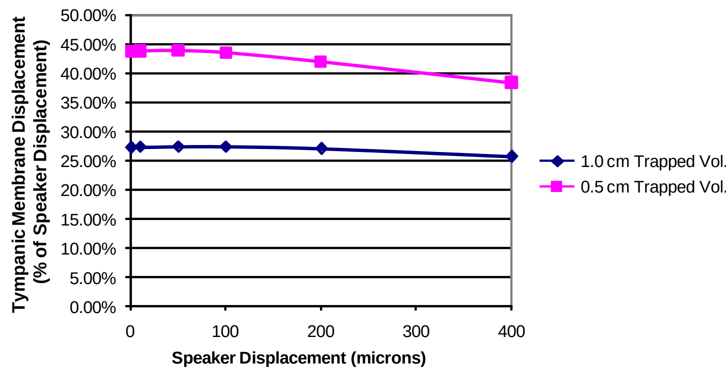


Figure 6: Tympanic Membrane Displacement Relative to Speaker Displacement, Expressed as a Percentage

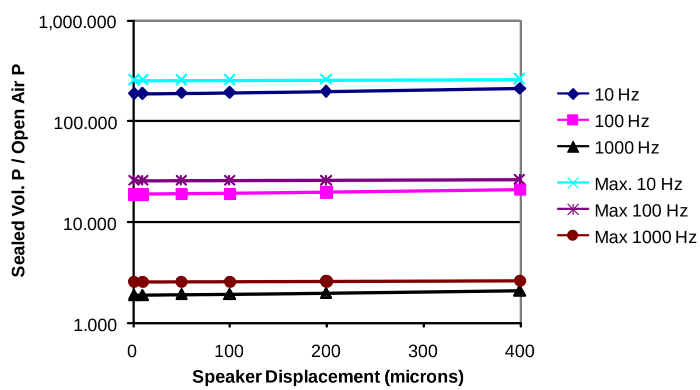


Figure 7: SPL in Sealed Volume Relative to Open Air

In Figure 7 the ratio of the sealed ear canal oscillating static pressure (peak or rms value) to the corresponding sound pressure (peak or rms value) that the same speaker would radiate in open air (measured directly in front of the diaphragm) is plotted vs. speaker displacement. The sealed volume oscillating static pressure is higher than the open air peak sound pressure across the entire range of speaker displacements. The maximum pressures that would occur if the tympanic membrane could not move are also plotted in this figure. These are equivalent to Figure 3 for Beranek's sealed, fully rigid tube. These values are always larger than the actual pressures generated in the ear canal. However the maximum pressures (Beranek model) in Figure 7 are important reference value*s* because they indicate the full magnitude of the static pressure driving force that is displacing the tympanic membrane. This pressure is not realized, however, because the tympanic membrane is already moving and relieving some of this static pressure before the speaker reaches its full displacement.

All the modeling in this section was couched in terms of positive excursions of the speaker and tympanic membrane that raise pressure in the trapped volume, above the normal, unperturbed air pressure in the ear canal. The converse analysis (in terms of negative excursions of the speaker and the tympanic membrane that lower the pressure in the trapped volume) yield similar results in terms of negative displacement of the tympanic membrane.

2.2.2. Oscillating Static Pressure Interacting with the Dynamics of the Middle Ear

Even though the pressure in the ear canal resulting from a sealed speaker in the ear is essentially uniform at any given instant, it is oscillating rapidly, and this has the potential to produce dynamic effects. In particular, the tympanic membrane and the structures attached to it have mass and inertia and therefore take a finite amount of time to respond to the pressure exerted on them, by the oscillating speaker diaphragm. This results in a phase lag between the driving speaker oscillation and the responding tympanic membrane oscillation. Additionally, the real structures of the tympanic membrane, the ossicular chain and the cochlea dissipate energy as they move (i.e. there is a small friction-like resistance to their motion). This damps the vibrational response of the tympanic membrane. The presence of these factors suggests that one should expect a frequency dependence to the oscillating static pressure in the trapped volume.

As discussed by Wada, Kobayashi and co-workers [18,19,26,27] the displacement of the tympanic membrane can be modeled with the following equation of motion:

$$m\,(d^2\delta/dt^2) \;+\; \zeta\,(d\delta/dt) \;+\; k\,\delta \;=\; S\,P\,\sin\omega t \qquad (5)$$

Here m is the mass of the tympanic membrane and other structures to which it is attached and which must move with it. The damping parameter ζ includes the damping influences of the tympanic membrane as well as the structures attached to it. The spring constant, k, includes the spring like resistance to displacement of the tympanic membrane and the structures attached to it. The displacement of the tympanic membrane at any given time, t, is given by the parameter δ. The first term on the left-hand-side of this equation represents Newton's law that force is equal to mass times acceleration. The second term adds the influence of damping or resistance, which is proportional to velocity. There is more resistance the faster one tries to move the tympanic membrane. The final term on the left-hand side gives the restoring, spring like, force associated with the elasticity of the motion the tympanic membrane and associated structures.

This equation has the form of *forced* mechanical vibrations with *damping*. The forcing function is provided by the oscillation of the speaker diaphragm, as transmitted to the tympanic membrane through the air in the trapped volume. This driving function (right-hand-side of Equation 5) is represented by a sine wave with angular frequency, ω, and an amplitude given by the product of S, the area of the tympanic membrane, and P, the pressure which drives the motion. The driving pressure is the maximum pressure that would be generated if the tympanic membrane were not able to move, equivalent to the Beranek sealed-tube model. This represents the total pressure driving force available to cause the motion of the tympanic membrane as governed by Equation 5.

Various literature references[17-19,25-29] provide information on the masses, damping characteristics, and spring constants of the tympanic membrane and all the various structures to which it is connected. These values were the results of measurements on live subjects and on cadavers, as well as detailed finite element, computer modeling studies. Using these component parameters, values of m, ζ, and k that are representative of the overall characteristics of the moving structure were calculated. These values, when used in Equation 5, produced calculated tympanic membrane displacements for open air hearing of around 10 nm for, 80 dB SPL in the frequency range from 100 to 1000 Hz. This agrees with the results in Figure 13 of Reference [25], thus confirming that this model produces realistic results for known conditions.

The solution to Equation 5 yields values for the amplitude of tympanic membrane displacement, δ, as well as the phase lag of tympanic membrane vibration relative to the oscillation of the driving (speaker) pressure. This solution is provided by Equations 3 and 4 of Reference [19]. Figure 8 shows tympanic membrane displacements in microns vs. frequency for the range of speaker displacements ranging from 1 micron to 400 microns for a 1 cm long trapped volume. The tympanic membrane displacements, which are on the order of microns to tens or hundreds of microns increase with speaker displacement, and are nearly constant for frequencies from 10 to 100 Hz. The values in this range are about the same as those obtained with the static pressure model for the same speaker displacements (Figure 5). The static pressure model does not contain a frequency dependence and is expected to be most similar to the dynamic model at low frequencies.

Figure 8 shows that at frequencies between 100 and 1000 Hz that the displacement starts to fall off with increasing frequency. This is due to the fact that at higher frequencies, inertial effects prevent the tympanic membrane and its associated structures from fully responding to the driving force before that force changes in magnitude and/or direction. Figure 9 shows the tympanic membrane displacement as a percentage of speaker displacement for a 1 cm long trapped volume and frequencies of 10, 100, and 1000 Hz. Compare this to Figure 6 for the static pressure model. The results in Figure 9 for 100 Hz are close in valve to those of the static pressure model. The tympanic membrane displacement as a percentage of speaker displacement is seen to be highly dependent on frequency. Lower frequencies producing higher percentage displacements and higher frequencies producing lower percentage displacements.

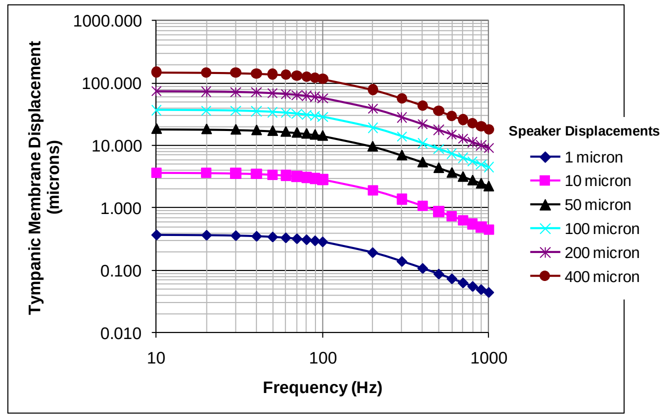


Figure 8: Tympanic Membrane Displacement as a Function of Frequency for a 1 cm Long Trapped Volume

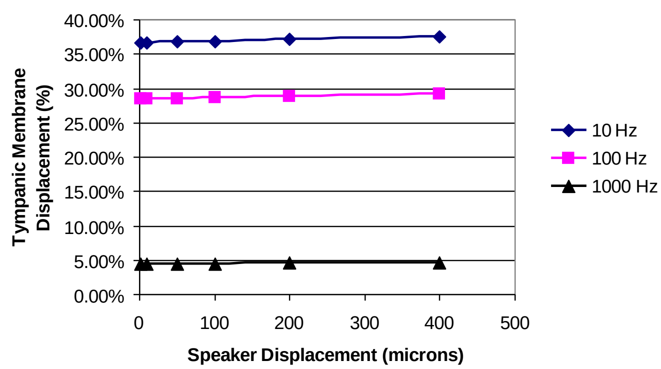


Figure 9: Dynamic Model Calculation of Tympanic Membrane Displacement as a Percentage of Speaker Displacement.

2.3. Summary and Conclusions from Modeling

Theoretical modeling of the relatively simple type applied here can generally capture or predict the major trends in a physical system. The exact values calculated for various parameters, such as tympanic membrane displacement and pressure in the ear canal, are less important than the order of magnitude and overall trends of these parameters. This is the case for a number of reasons: There is variability in the size and mechanical properties of the middle ear structures in the human population[29], and thus theoretically calculated values or experimental values obtained from individuals or averages of individuals, are not likely to match those found in any particular other individual. This also applies to the parameters m, ζ, and k used in the dynamic modeling calculations. The parameters used were based on measurements on groups of human subjects and on fitting of model calculations to data obtained from human subjects[17-19,25-29]. These parameters do not necessarily apply perfectly to any given individual.

The models used are relatively simple and thus cannot take into account the full complexity of the natural systems that they are simulating. The hope is that the models capture enough of the essence of what makes the physical system work to provide some predictions of trends and the magnitude of responses. Understanding the full complexities of these systems would require a very involved and very detailed model, such as the finite element modeling of Wada and co-workers [19,25] to capture.

The models agree on the main conclusions of the study. Sealing a speaker in the ear can produce dramatic over excursions of the tympanic membrane on the order of a micron up to tens or even hundreds of microns depending upon the speaker displacement. This is 100 to 1000 or more times the normal excursions of the tympanic membrane in open ear hearing. This occurs because the trapped volume of air in the ear canal acts as a pneumatic air piston with a rapidly oscillating static pressure.

The magnitude of the over excursions obtained from the static model (Figure 5) agree quite well in size to those found for the dynamic model in the low frequency range (10 to 100 Hz) in Figure 8. This reinforces the validity of both models and is expected since the assumptions of the static model are most applicable to the dynamic model at low frequencies (i.e. when it is most static). At higher frequencies the dynamic model (Figure 8) shows a drop off in tympanic membrane displacement. The static pressure oscillations in the trapped volume of the ear canal can produce very high SPL especially at lower frequencies, and these static pressure oscillations are distinct from open air sound waves because their pressure oscillations are 90 degrees out of phase with velocity components. Normal, open air sound waves have their pressure oscillations in phase with their velocity components.

3. IMPACTS ON THE LISTENING EXPERIENCE

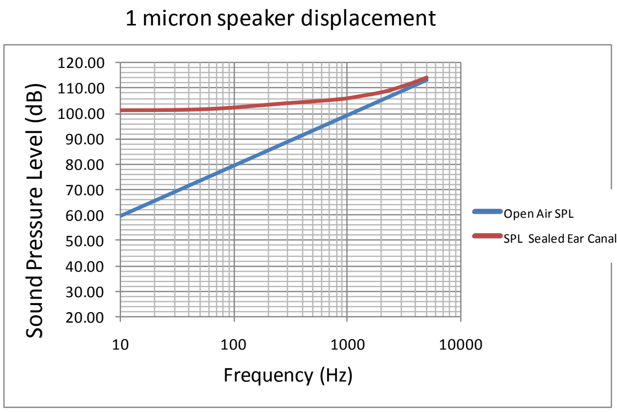
As stated above, it seems likely that static pressure oscillations in the ear canal and the resultant over-excursions of the tympanic membrane trigger the stapedius reflex, contribute to listener fatigue, and may, through long term exposure, contribute to hearing damage.

3.1. Trapped Volume Insertion Gain

Audiologists refer to a phenomena known as ***insertion gain***.[30,31] This is an increase in the SPL, especially of lower frequencies when a device, such as a hearing aid is sealed in the ear. Insertion gain is frequently measured by a probe microphone inserted into the sealed volume between the speaker and the tympanic membrane. An audiologist will typically adjust the frequency response of a device, such as a hearing aid, in order to compensate for the insertion gain. Here we define a variant of this phenomenon, which we call ***Trapped Volume Insertion Gain (TVIG)***, and show the TVIG to be largely, or perhaps exclusively, the result of the high amplitude static pressure oscillations in the trapped volume of the ear canal described above. The TVIG is the difference between the SPL in the sealed ear canal vs. the SPL when the speaker is held in approximately the same position but not sealed with an airtight seal. This is also approximately the same as the difference between the SPL in the sealed ear canal and the SPL that the sound wave would produce in open air.

Figure 10 shows plots of SPL in a simulated, sealed ear canal vs. frequency. For comparison, open air SPL (not including any closed volume static pressure effects) is also plotted for the same frequencies and speaker displacements. These results for sealed-ear SPL were calculated from the dynamic model of the previous section. At each frequency, the TVIG, plotted in Figure 11, is the difference between the total SPL in the sealed ear canal, including the effect of static pressure oscillations, minus the open air SPL, which would result from the same speaker motion. Below about 2000-3000 Hz, the oscillating static pressure boosts the overall SPL in the ear canal above the level associated with the open air acoustic waves. This static pressure boost decreases with increasing frequency.

(a)



(b)

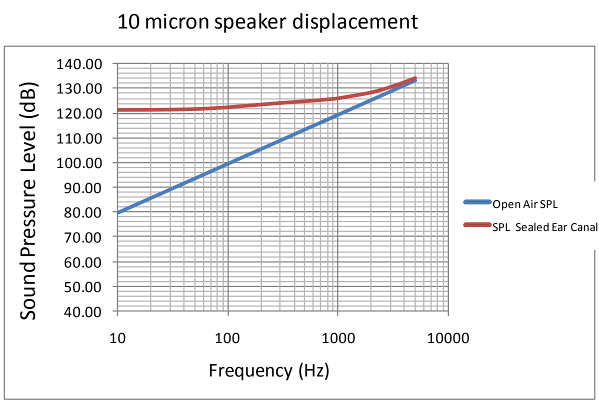


Figure 10: Model Calculations Comparing SPL in a Sealed Ear Canal vs. Unsealed. (a) 1 micron speaker displacement, (b) 10 micron speaker displacement

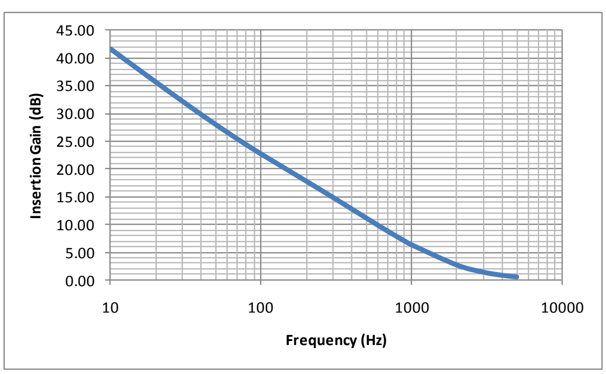


Figure 11: Trapped Volume Insertion Gain (TVIG) Calculated From Fig. 10.

3.2. Measurements on a Speaker Sealed in the Ear

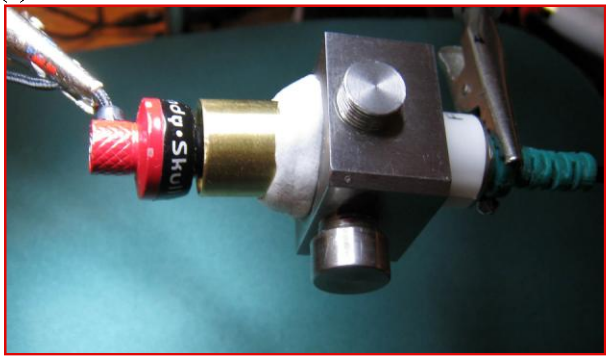
The trends of displacement vs. frequency shown in Figure 8 for the dynamic model are born out experimentally by studies involving insert ear tips (ear buds) sealed in a Zwislocki Coupler and also sealed in a human ear.

Commercially available insert ear tips (Skullcandy) were used in this study, in which they were sealed either into a Zwislocki coupler or into a human ear canal. In these tests, tones of various frequency as well as other audio clips were played through the ear tips. A small probe microphone (Knowles FG) is placed in the Zwislocki coupler or in the human subject's ear canal to record relative sound pressure level SPL as it exists in front of the ear drum. The lead for this probe microphone is threaded through the acoustic seal of the ear-tip, without breaking the airtight seal,

An experiment was performed to measure the increase in low frequency amplitude, or ***Trapped Volume Insertion Gain (TVIG)***, when a speaker is sealed into the ear canal. Figure 12 shows the experimental set up. In Figure 12a an ear-tip is inserted into the Zwislocki coupler but is not sealed with an air-tight seal. In Figure 12b, the same ear-tip is sealed in the coupler. The depth of insertion into the coupler, with and without a seal, is the same. Relative SPL was measured in the coupler across a frequency spectrum from 20 to 20,000 Hz for both the sealed and the unsealed condition.

Figure 13a shows SPL vs. frequency, for the sealed and unsealed conditions, for the identical input to the speaker. Clearly, there is a large boost in the low frequencies in the sealed over the unsealed case. The experimental data below about 2000 to 3000 Hz is remarkably similar to the modeling results in Figure 10. The calculations behind Figure 10 are based on the dominant influence of oscillating static pressure at low frequencies. Figure 13b plots the experimentally determined TVIG calculated by subtracting the curve in Figure 13a for the unsealed condition from that for the sealed condition. Figure 14 shows the experimentally determined TVIG plotted along with the theoretically calculated values (reproduction of Figure 11). The agreement between the experimental data and the model, based on oscillating static pressure in a sealed ear canal, is quite good, especially considering that the

(a)



(b)

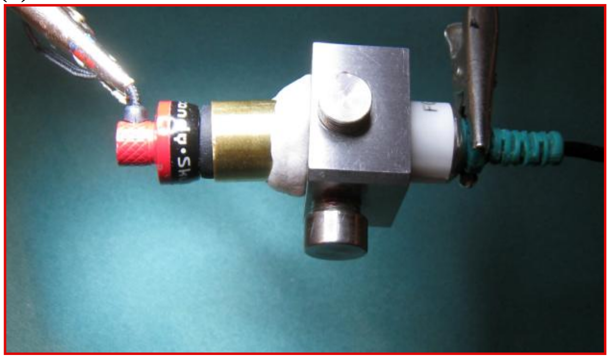
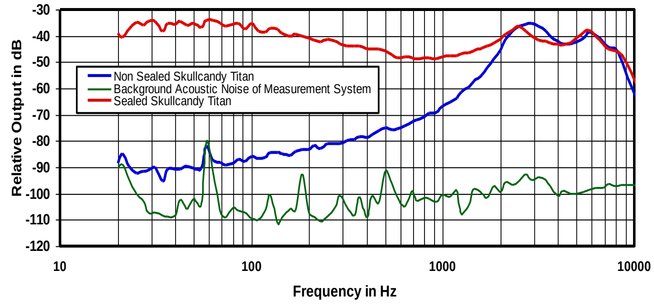


Figure 12: Ear-Tip in Zwislocki Coupler for TVIG

(a)



(b)

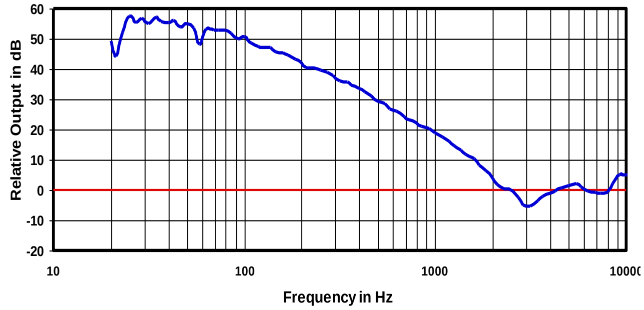


Figure 13: Measurement of TVIG. (a)Measurements of Unsealed and Sealed SPL, (b) TVIG Calculated From Measurements

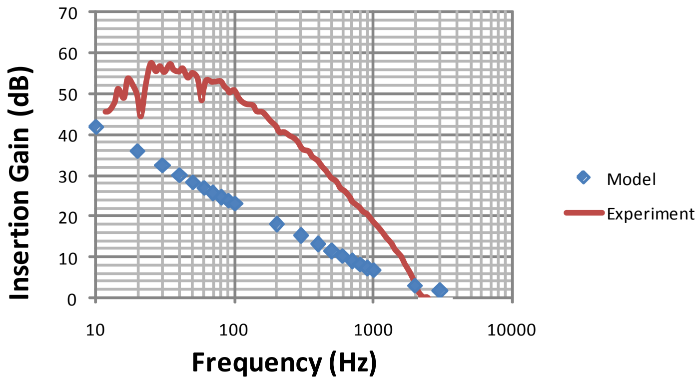


Figure 14: Comparison of Calculated and Measured Trapped Volume Insertion Gain (TVIG)

ear canal dimensions and characteristics used in the modeling do not exactly match those of the Zwislocki coupler. This general agreement with experiment speaks to the validity of the underlying physical understanding, oscillating static pressure, on which the model is based.

For comparison to our experimental data in Figure 13, recently published data on a very similar experiment using insert headphones in a simulated ear canal, yielded very similar results.[21] This included showing that the gain effect is much larger at smaller trapped volumes than at larger trapped volumes. This agrees with the results of our oscillating static pressure model.

Using the same experimental setup as in Figure 12 (i.e. identical ear tip insertion into a Zwislocki coupler, comparing sealed to unsealed conditions), the relative phase of the sound/pressure waves in the sealed volume was compared for sealed vs. unsealed conditions. The results are shown in Figure 15. As expected the relative phase difference between the sealed and unsealed condition at the lowest frequencies is about 90 degrees because the oscillating static pressure, in the sealed case, follows maximum speaker displacement, while in the unsealed case the acoustic wave maxima track the maximum speaker velocity, which occurs at zero speaker displacement.

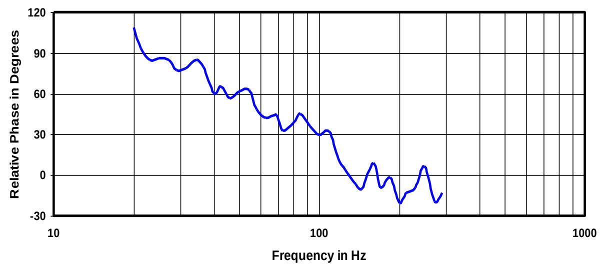


Figure 15: Phase Difference Between Sealed and Unseal Ear-Tip

3.3. The Stapedius Reflex

The dynamic range of the human cochlea is about 30% narrower than the range of sound pressure levels that can be heard. Louder sounds, above around 80 to 90 dB, are compressed to fit into the dynamic range of the cochlea by a response of the middle ear known as the *Stapedius Reflex*. In response to loud sounds, the stapedius muscle, which is connected to the stapes (stirrup) bone of the middle ear, contracts and thereby tightens the tympanic membrane. The contraction of the stapedius muscle also repositions the ossicles to pull the stirrup back, reducing the amplitude of motions transferred to the oval window of the inner ear. These mechanical adjustments to the middle ear reduce its sensitivity and thus allow it to process louder sounds. This is a bit like switching from the "fine" to the "coarse" setting on a sensing device such as a voltmeter. The coarse setting allows much larger signals to be measured, but at the cost of reducing the sensitivity to small changes in the signal.

The fact that the stapedius reflex reduces our sensitivity to sounds at moderate sound pressure levels can be appreciated because of the *vocalization-induced stapedius reflex.*[32] When a person speaks they automatically trigger a tensioning of the stapedius muscle which reduces the perceived amplitude of outside sound reaching the ear by about 20 dB, even if that sound is not loud enough to trigger the stapedius reflex itself.

Numerous studies have been reported that measure the onset or threshold SPL above which the stapedius reflex occurs.[7-14] This threshold, in humans, has been reported to be as low as 60 dB and as high as 90dB. Above this threshold tightening of the stapedius muscle, compresses dynamic range. The stapedius reflex threshold is relatively uniform across a broad range of frequencies and falls in the 70 to 90 dB range for people with normal hearing. If anything, the stapedius threshold appears to be a little lower at lower frequencies than at higher frequencies, registering as about 75 dB at 125 Hz.[10]

The stapedius reflex, triggered by the high TVIG induced SPL in the sealed ear canal at low frequencies, may be a major contributor to audio (listener) fatigue, and may produce a diminishment of the quality of the listening experience. As shown above, through modeling and through experiments, sealing a speaker in the ear, as is done with insert headphones or hearing aids, results in oscillating static pressures in the ear canal, which can also be interpreted as equivalent SPL, and which produce abnormally large excursions of the tympanic membrane. At even moderate listening volumes, the TVIG at lower frequencies can easily push the SPL in the ear canal above the stapedius reflex threshold, which is about 75 dB at 100 Hz. Other studies report this threshold to be as low as 60 dB, and of course there is variation from individual to individual.[7-14]

Figure 10 shows modeling results indicating that playing audio, which would yield an SPL of 60 dB in open air, yields an SPL of over 100 dB in a sealed ear canal. This boosted SPL in the trapped volume would certainly trigger the stapedius reflex in an individual with normal hearing. Figure 13a shows experimental data in which the SPL produced by an insert headphone sealed in the ear (red curve) is as high as 75 dB at 100 Hz and below. Absolute SPL values are obtained by subtracting the green background (taken as zero dB) from the graph of interest. Note that this experiment was actually performed at very low sound levels as indicated by the unsealed earbud data (blue curve), which is at only about 20 to 25 dB at 100Hz and below. These low open air sound levels were used in the experiment of Figure 13a so that the large TVIG upon sealing the speaker in the coupler did not produce SPLs that exceed the linear response range of the inserted measurement microphone. Never-the-less, the data in Figure 13a shows sealing in the ear can boost a whisper-quiet speaker output to a level where it can trigger the stapedius reflex.

If a person is listening to insert headphones at what would be considered a normal level, it is very likely that the low frequency content of the audio will produce oscillating, high amplitude pressures in the ear canal, which will trigger the stapedius reflex. This can have a number of deleterious effects: The stiffening of the oscular chain and the tympanic membrane brought about by the stapedius reflex reduce the sensitivity of the hearing system to other frequencies (especially in the midrange), which may not be boosted above the stapedius reflex threshold. To use the voltmeter analogy, the booming, trapped volume, bass turns the meter on “coarse,” which then means that it does a poorer job registering the smaller nuances and variations of the signal at other frequencies.

Also, the stapedius muscle is like any other muscle in the body in that it will fatigue from over use. It is possible that this is a major cause of the listener fatigue reported by some users for insert headphones. In the natural conditions under which humans evolved, the stapedius reflex would likely be triggered somewhat rarely and not for extended periods of time. A person listening to insert headphones, however, may be placing their stapedius muscle in an unnatural state of over exertion. This will fatigue the muscle and perhaps other tissues in the ear to which it is connected.

3.4. Infrasound

Sound at frequencies lower than 20 Hz is known as infrasound.[33,34] Most people cannot hear these very low frequencies, but may feel them as vibrations. Although the experimental results presented above were only measured down to 20 Hz, the top end of this range, it is clear that insert headphones of the type tested will be able to produce frequencies in the infrasound range. Additionally, the trapped volume effect of the ear canal will boost these infrasound frequencies via oscillating static pressure effects. The infrasound content of recorded music and other audio material is not typically reported, but measurements reveal the presence of significant spectral content below 10 Hz. Normal, open air sound equipment like home and car stereo systems typically cannot produce much output volume below about 50 Hz, and thus the low frequency content of recordings is not commonly heard. However, insert headphone, can produce these low frequencies, and these frequencies are dramatically boosted by static pressure oscillations in closed volumes, such as the ear canal. Exposure to infrasound has been linked to illness and health problems,[34] and is even the basis for sonic weapons.[34] The use of headphones sealed in the ear may be exposing people to infrasound.

4. MITIGATIONS OF NEGATIVE EFFECTS OF SEALING A SPEAKER IN THE EAR

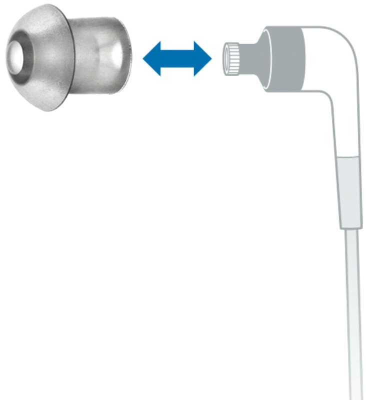
The large amplitude pressure oscillations resulting when a sound producing device is sealed in the ear canal produce a range of deleterious effects on the quality of the listening experience, and on listener comfort, and potentially on long term health (mainly hearing health, but also health in general through the potential influences of exposure to infrasound). Some in-ear listening devices such as hearing aids and in-ear monitors for musicians require an acoustic seal in the ear to prevent feedback from nearby microphones. Thus it is not always desirable or possible to get rid of the static pressure oscillations and over-excursions of the tympanic membrane by breaking the ear seal or adding a vent to allow communication with the open air. It is therefore of great utility to mitigate the effects of oscillating static pressure and the resulting over-excursions of the tympanic membrane while maintaining an acoustical seal in the ear.

Here we present experimental evidence that a compliant surface added to some part of the enclosure creating the trapped volume in the ear canal acts to reduces trapped volume insertion gain (TVIG) and thus may prevent the excitation of the stapedius reflex.

One approach to achieving this is the use of an inflatable ear seal with a compliant surface.[35,36] Another approach, which is discussed here, is a vent in an ear seal that is covered by a thin flexible membrane allows the relief of static pressure build up (including both positive and negative pressures), through deformation of the thin flexible membrane. This deformation of the covering of the vent may include expansion or contraction; bowing out or bowing in; and performing these motions as vibrations at acoustical frequencies. Alternatively the function of the covered vents may be described as the radiating of excessive, low frequency, acoustical energy out of the sealed volume of the ear canal. Either description leads to the same function for the covered vents: to reduce pressure and SPL in the ear canal so as to reduce over excursions of the tympanic membrane and to prevent to stapedius reflex.

Ear buds or insert headphone tips often have structures as illustrated in Figure 16. Figure 16a shows how the insert headphone tip slips over the snout of the earphone body. Figure 16b shows the structure of a typical insert headphone tip. A hollow, sound tube connects the sound

(a)



(b)

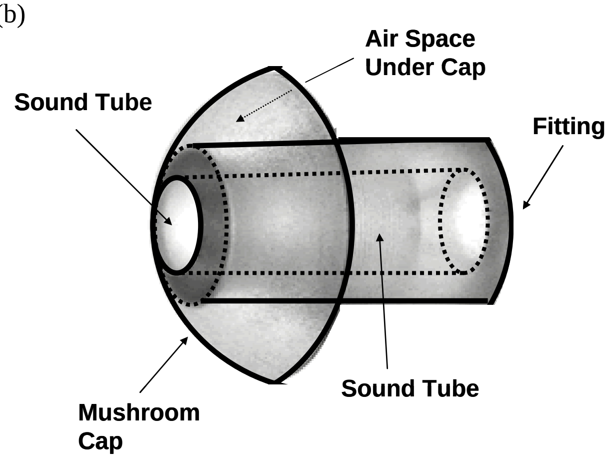
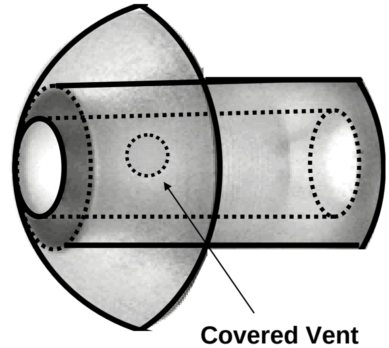


Figure 16: Insert Ear Phone, (a) Sealing Ear-Tip Fitting to Housing, (b) Detail of Sealing Ear-Tip

(a)



(b)

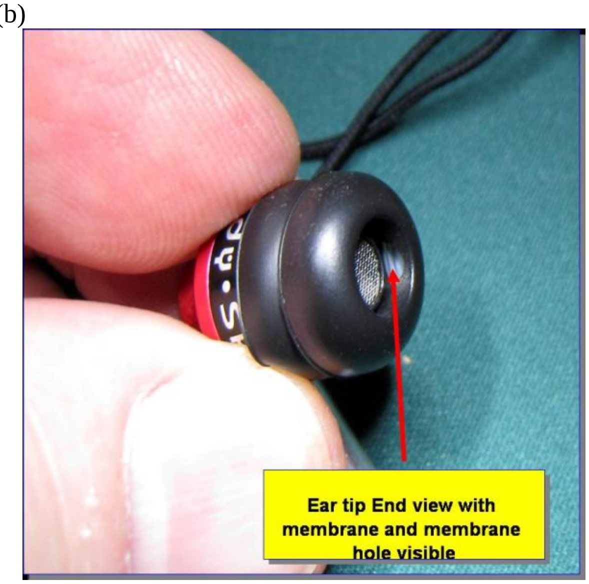


Figure 17: Insert Ear-Tip Modified with Covered Vent, (a)Schematic, (b) Photograph

source in the earphone body, through the ear tip, into the ear canal. The acoustic seal is provided by a “mushroom cap” structure which flares out around the end of the sound tube facing into the ear canal. There is an open (air filled) space underneath the mushroom cap, i.e. between the underside of the mushroom cap and the outside of the sound tube.

Figure 17a shows a schematic of an insert ear-tip modified to include a covered vent in its sound tube. A hole, or multiple holes, in the sound tube are covered by a flexible membrane material to produce a covered vent or multiple covered vents. The flexible membrane material covering the vents should be very light and flexible, and is typically a polymer material such as expanded polytetrfluoroethylene (ePTFE). The Scullcandy insert ear tips, analyzed above, were modified to add a covered vent to the sound tube as shown in Figure 17b. The ePTFE covered vent is visible from the inside of the sound tube.

Figure 18 shows the results of testing on this ear tip with a covered vent. It shows the relative SPL vs. frequency for the ear tip with the covered vent as compared to the same type of ear tip without the covered vent, both sealed in a human ear canal. There is a clearly a marked reduction in relative SPL for frequencies below 3000 Hz, showing the ear tip with a covered vent reduces static pressure oscillation in the ear canal, and therefore reduces SPL and over-excursions of the tympanic membrane. Reductions of 5 to 20 dB were brought about by the inclusion of a single

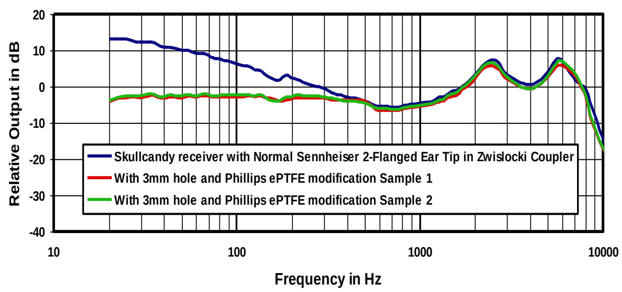


Figure 18: Comparison of SPL Levels in a Human Ear Canal when Sealed with a Conventional Ear Tip (blue), and an Ear Tip with a Covered Vent (green & red).

covered vent in the ear tip. This reduction in the trapped volume insertion gain has a strong likelihood of preventing the stapedius reflex under normal listening conditions, and thereby preventing audio fatigue and potentially preventing long term hearing damage.

5. SUMMARY AND CONCLUSIONS

When a sound producing device such as insert eartips or a hearing aid is sealed in the ear canal, the trapped volume of air in the ear canal acts like a pneumatic piston, which transmits an oscillating static pressure to the tympanic membrane. This effect greatly boosts the SPL in the ear canal, especially a low frequencies, a phenomena which we call Trapped Volume Insertion Gain (TVIG). Even at moderate listening volumes, the TVIG can increase the low frequency SPL in the ear canal above the threshold necessary to trigger the Stapedius reflex, a stiffing response of the middle ear, which reduces its sensitivity, and may lead to audio fatigue. The addition of a covered vent in the sound tube of an insert ear tip was found to reduce the TVIG, such that the Stapedius reflex would likely not be triggered.

6. ACKNOWLEDGEMENTS

SDA would like to thank his co-authors SPG and RBS for translating his intuitive understanding of sound reproduction in a closed ear canal into a scientific and mathematical explanation, and for conducting controlled experiments to confirm and quantify these effects. All the authors wish to thank Jay Kadis (Stanford University), for insights regarding the middle ear and review of early results of this study. The authors wish to thank Larry Purcell for helpful discussions and support. This work was funded by Asius Technologies and by the United States National Science Foundation (NSF) under Small Business Innovative Research (SBIR) contract 1046625.

7. REFERENCES

[1] Beginning in the 1960's, as a teenager, Stephen D. Ambrose began building the first rudimentary, in-ear monitors, based on modifications of a 3M Wollensak reel-to-reel tape recorder and crystal radio earpieces, modified with "ear molds" made out of modeling clay, for his own use as a musical performer. Ambrose's 1972 solo album, *Gypsy Moth*,(Barnaby Records 1972) was likely the first recording written and rehearsed with the aid of in-ear monitors. While touring, and performing on live radio, in support of this album, Ambrose continued to refine the design of in-ear monitors, and in 1976, Ambrose wore the first custom molded, truly high fidelity in-ear monitors while performing in Hollywood, California. Beginning in 1976, Ambrose began to manufacture and market the first commercially available in-ear monitors, and by 1978 he featured the devices at the Anaheim NAMM Show under his company's name, SoundSight Micro-Mics and Micro-Monitors. Ambrose's wireless in-ear monitors were first widely embraced by the Hollywood film scoring industry, to record soundtracks for films such as *Star Trek*, *Escape from Alcatraz*, *ET* and hundreds more. From there, the popularity of the in-ear monitors spread to popular music; Ambrose spent most of the 1980's working one-on-one with a long list of artists, in the studio and on tour, providing custom in-ear monitoring, micro-mics, and other novel audio technology. Among Ambrose's first and most loyal clients was Stevie Wonder, as well Simon and Garfunkle, who engaged Ambrose to provide customized in-ear monitoring and on-site support for their two year, four continent, reunion tour in the early 1980's.

[2] David Zimmer "Micromonitors in Your Ear" *BAM: The California Music Magazine*; May 21, 1982. p. 38. (Article about Stephen Ambrose and his in-ear monitors.)

[3] S. D. Ambrose "High Fidelity Earphone and Hearing Aid" U.S. Patent 4,852,177; July 24, 1989.

[4] W. L. Creten and K. J. Van Camp. "Transient and Quasi-Static Tympanometry" *Scand Audiol* 3: 3942. 1974.

[5] Y.W. Liu, C. A. Sanford, J. C. Ellison, D. F. Fitzpatrick, M.P. Gorga, D. H. Keefe. "Wideband absorbance tympanometry using pressure sweeps:

System development and results on adults with normal hearing" *J. Acoust. Soc. Am.* 124(6), December 2008. pp. 3708-3719.

[6] G. Liden, E. Harford, O. Hallen. "Automatic Tympanometry in Clinical Practice" *Audiology* 13: 126-139 (1974).

[7] J.-E. Zakrisson, and E. Borg. "Stapedius Reflex and Auditory Fatigue" *Audiology* 13: 231-235 (1974).

[8] U. Reker. "Normal Values of the Ipsilateral Acoustic Stapedius Reflex Threshold" Arch. Oto-Rhino-Laryng. 215, 25-34 (1977).

[9] L. J. Deutsch."The Threshold of the Stepedius Reflex for Pure Tone and Noise Stimuli" *Acta Otolaryng* 74: 248-251, 1972

[10] J. Bergenius, E. Borg, and A. Hirsch. "Stapedius Reflex Test, Brainstem Audiometry and Opto-Vestibular Tests in Diagnosis of Acoustic Neurinomas" *Scand Audiol* 12: 3-9, 1983

[11] C. A. Mangham, J. M. Miller. "A Case for Further Quantification of the Stapedius Reflex" *Arch Otolaryngol* Vol. 105, 593-596, 1979.

[12] G. Laurell, and M. Skedinger. "Changes of Stapedius Reflex and Hearing Threshold in Patients Receiving High-Dose Cisplatin Treatment" *Audiology* 1990; 29, 252-261.

[13] S. A. Counter. "Brainstem mediation of the stapedius muscle reflex in hydranencephaly" *Acta Oto-Laryngologica*, 2007; 127: 498-504

[14] J. J. Zwislocki "Auditory system: Peripheral nonlinearity and central additivity, as revealed in the human stapedius-muscle reflex" *PNAS* October 29, 2002: vol. 99: no. 22: 14601–14606.

[15] Leo L. Beranek *Acoustics* (New York: McGraw-Hill, 1954). Section 2.4, pp. 28-35

[16] M. C. Junger, and D. Feit. *Sound, Structures, and Their Interaction*. (Cambridge, Massachusetts: The MIT Press, 1972, 1986). p. 20, Equation 2.8.

[17] N. Yamamoto, T. Ishii, and T. Machida. "Measurement of the Mechanical Properties of the Tympanic Membrane with a Microtension Tester" *Acta Otolaryngol (Stockh)* 1990; 110: 85-91.

[18] H. Wada, and T. Kobayashi "Dynamical behavior of middle ear: Theoretical study corresponding to measurement results obtained by a newly developed measuring apparatus" *J. Acoust. Soc. Am.* 1990, 87, 237.

[19] H. Wada, T. Metoki, and T. Kobayashi "Analysis of dynamic behavior of human middle ear using a finite-element method" *J. Acoust. Soc. Am.* 1992, 92, 3157.

[20] J.-Y. Ahn, H. J. Park, G.-H. Park, Y.-S. Jeong, H.-B. Kwak, Y.-J. Lee, J.-E. Shin, W.-J. Moon. "Tympanometry and CT Measurement of Middle Ear Volumes in Patients with Unilateral Chronic Otitis Media" Clinical and Experimental Otorhinolaryngology Vol. 1, No. 3: 139-142, September 2008

[21] M. Hiipakka, M. Tikander, and M. Karjalainen "Modeling of External Ear Acoustics for Insert Headphone Usage" *J. Audio Eng. Soc.*, Vol. 58, No. 4, 2010, pp. 269-281.

[22] R. H. Perry and C. H. Chilton editors. *The Chemical Engineers' Handbook, 5th Edition* (New York: McGraw Hill, 1973) p. **3**-105, Table 3-159.

[23] A. L. Flory, D. A. Brass, and K. R. Shull. "Deformation and Adhesive Contact of Elastomeric Membranes" *Journal of Polymer Science: Part B: Polymer Physics*, Vol. 45, 3361–3374 (2007).

[24] H. Wada, M. Ando, M. Takeuchi, H. Sugawara,T. Koike, T, Kobayashi, K. Hozawa, T. Gemma, M. Nara. "Vibration measurement of the tympanic membrane of guinea pig temporal bones using time-averaged speckle pattern interferometry" *J. Acoust. Soc. Am.* 111 (5), Pt. 1, May 2002. pp. 2189-2199.

[25] T. Koike, H. Wada, T. Kobayashi. "Modeling of the human middle ear using the finite-element method" J. Acoust. Soc. Am. 111 (3), March 2002, pp. 1306-1317.

[26] H. Wada, K. Ohyama, T. Kobayashi, T. Koike, S. Noguchi. "Effect of Middle Ear on Otoacoustic Emissions" *Audiology* 1995, 34, 161-176

[27] H. Wada, K. Ohyama, T. Kobayashi, N. Sunaga, T. Koike. "Relationship between Evoked and Otoacoustic Emissions and Middle Ear Dynamic Characteristics" *Audiology* 1993, 32, 282-292.

[28] T. Koike, H. Wada, T. Kobayashi "Effect of Depth of Conical-Shaped Tympanic Membrane on Middle-Ear Sound Transmission" JSME International Journal 2001, 44, 1097-1102.

[29] T. Koike, M. Shinozaki, S. Murakami, K. Homma, T. Kobayashi, H. Wada. "Effects of Individual Differences in Size and Mobility of the Middle Ear on Hearing" JSME International Journal 2005, 48(4), 521-528.

[30] A. Baumfield, L. Hickson, and B. McPherson. "Performance of Assistive Listening Devices Using

Insertion Gain Measures" *Scand Audio1*. 1993; 22: 43-46

[31] R. C. Seewald, L. E. Cornelisse, S. L. Black, and M. G. Block. "Verifying the Real-Ear Gain in CIC Instruments" The Hearing Journal 1996, 49(6), 25-33.

[32] http://en.wikipedia.org/wiki/Acoustic_reflex

[33] H. Moller, C.S. Pedersen "Hearing at low and infrasonic frequencies" Noise and Health 2004, 6(23), pp. 37-57.

[34] K. E. Haneke, B. L. Carson, C. A. Gregorio,E. A. Maull *Infrasound: Brief Review of Toxicological Literature*, November 2001. Report of the National Toxicology Program under Contract Number N01-ES-65402.

[35] Stephen D. Ambrose, Samuel P. Gido, Jimmy W. Mays, Roland Weidisch, Robert Schulein. "Diaphonic Acoustic Transduction Coupler and Ear Bud." U. S. Patent Application US2009/0028356 A1

[36] Stephen D. Ambrose, Samuel P. Gido, Robert Schulein. " Inflatable Ear Device." U. S. Patent Application 12/777,001, May 10, 2010.

[37] Stephen D. Ambrose, Samuel P. Gido, Robert Schulein. "Hearing Apparatus and Method" U. S. Provisional Patent Application 61/409,724, November 3, 2010.