Proceedings of Meetings on Acoustics

ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Engineering Acoustics
Session 4pEAa: Sound Field Control in the Ear Canal

4pEAa4.   Mitigation of excessive acoustic compliance and trapped volume insertion gain in ear-sealing listening devices

Stephen D. Ambrose*, Samuel P. Gido and Todd Ricketts

 *Corresponding author's address: Asius Technologies, LLC, 1257 Whitehall Drive, Longmont, CO, CO 80504, stephen.ambrose@asiustechnologies.com

  When a sound producing device is sealed in the ear canal, acoustical compliances resulting from pressurization of the trapped volume lead to dramatic boosts in SPL, up to 60 dB, especially at low frequencies. This has been found to result in listener fatigue, and to trigger the acoustic (stapedius) reflex, as well as producing temporary threshold shift. Repeated exposure can cause temporary threshold shift to become permanent. Hearing aids avoid this problem by suppressing frequencies below about 300 Hz, where the effect is most pronounced. Other devices such as ear buds and professional in-ear monitors, offer wider frequency response and thus expose listeners to potentially dangerous sound pressures. The trapped volume insertion gain is measured for ear buds by comparing SPL, measured in the ear canal, for sealed and unsealed conditions. New ear sealing technology is demonstrated that allows release of the excess acoustical compliance and thus mitigates the trapped volume insertion gain: (1) a vent covered with a flexible membrane, and (2) an inflatable bubble seal.

Published by the Acoustical Society of America through the American Institute of Physics

INTRODUCTION

From the 1960's to the present, Stephen D. Ambrose has been investigating and developing improved technology for coupling sound into the human ear. 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.[1] 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[2], providing partial solutions. The present paper explores scientific explanations 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 very high sound pressure levels 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. Under acoustic compliance dominated conditions, 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, pneumatic pressure, like the pressure confined in an inflated balloon or the static pressure employed in Tympanometry[3-5]. But, paradoxically, this static, pneumatic pressure is also changing very rapidly, i.e. it is oscillating at acoustical frequencies.

Here we also discuss a new approach to mitigating 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 pneumatic 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.

PNEUMATIC VS. ACOUSTIC COUPLING OF SOUND TO THE EAR

The mechanism by which power from the speaker is imparted into the small volume of air in the ear canal is fundamentally changed when the device is sealed in the ear. In open air, the power is free to radiate away from the speaker and does not build up, the resultant sound pressure (in Pascals) is proportional to $(zW)^{1/2}$, where z is the characteristic impedance and W is the power of the speaker. When the speaker seals a small, trapped volume in the ear, power may be imparted to the air by compressing it (a compliance) or translating it (an inertance). In the case of compliance the air pressure generated is $W/(Vv)$ where V is the trapped volume in the ear canal and v is the frequency of speaker motion. Because the acoustic compliance and inertance are analogous to a mass (intertance) oscillating on a spring (compliance), the two forms of energy, compression and translational motion, can be traded back and forth while energy is conserved (neglecting acoustic resistance losses). Thus the relationship between power and compression generated air pressure is valid for the sealed ear case no matter how the behavior is partitioned at any given instant between acoustic compliance and acoustic inertance.

This difference in the mechanism by which power is coupled into the sealed vs. nonsealed ear canal can produces a dramatic increase in sound pressure levels (SPL) in the sealed case, 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*[6-13]. 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. Additionally, exposure to high sound pressure levels in the sealed ear canals of hearing aid wearers has been shown to produce temporary (hearing) threshold shift and over prolonged exposure can lead to permanent threshold shift, i.e. permanent hearing damage.[14-19] These effects are also beginning to be appreciated as a hearing health risk associated with ear-sealing headphones (ear buds) for recreational listening, especially when high listening volumes are present.

The difference between the acoustic (open air) and the pneumatic (sealed ear canal) mechanisms by which power is imparted into the ear canal allows a simple calculation to estimate the trapped volume insertion gain (TVIG). This

calculation is based on the power coupling mechanism alone, taking no account of the detailed properties of the ear or the speaker, yet it comes remarkably close to predicting TVIG values obtained via experiment and more detailed calculations. Figure 1 plots TVIG as a function of speaker power output for frequencies ranging from 20 to 3000 Hz. Not only do the TVIG values agree quite well with measurements, but the fact that TVIG becomes negligible above 3000 Hz also agrees with experiment and more detailed modeling.
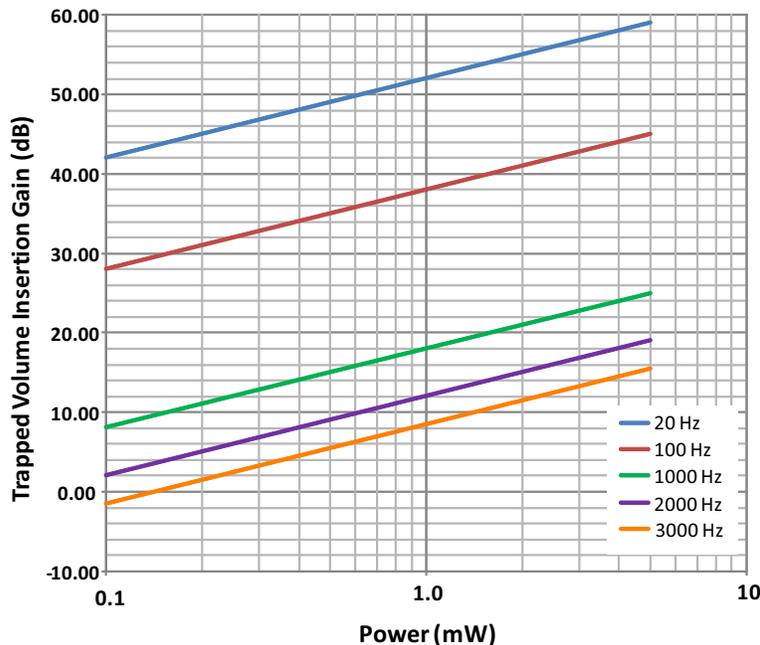
FIGURE 1: Trapped Volume Insertion Gain (TVIG) as a function of speaker power

The oscillating pneumatic pressure (acoustic compliance and inertance) 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 counterproductive 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 and or producing a temporary or permanent threshold shift.

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), 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 propagation in open air).

Beranek, analyzed the case of a rigid piston oscillating in one end of a rigid tube, which is closed on the opposite end.[20] 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, which give the pressure profiles along the length of the tube, are equally applicable to very short tubes. Figure 2 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).

Pressures used in these calculations are in Pascals not the logarithmic dB scale. 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.
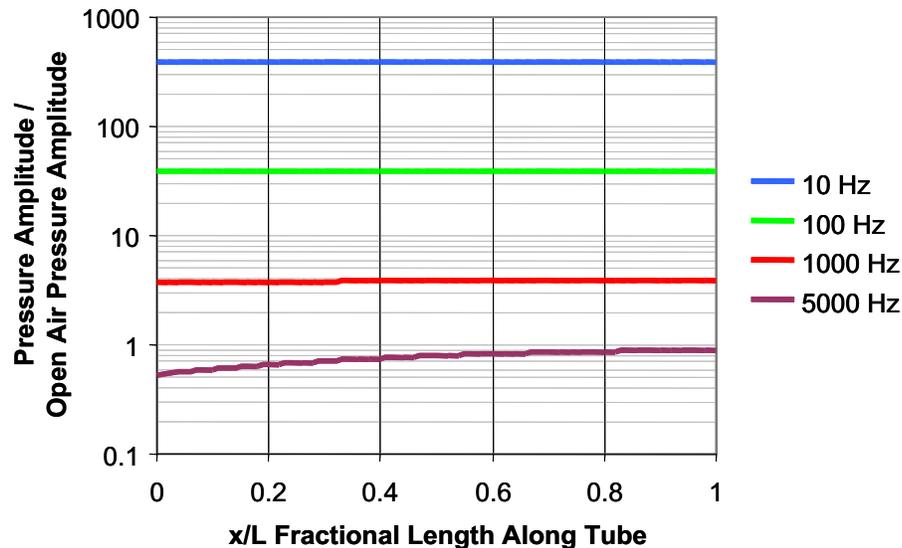

FIGURE 2: Pressure Profiles Along a 1cm Long, Rigid Tube with a Vibrating Piston in the End.

Of course the pressure is also oscillating in time. Figure 2 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 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 fact that the pressure profile in the short tube is quasi-static and thus may be analyzed as a pneumatic 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 pneumatic pressure: $P = B (\Delta V/V)$, where B is the bulk modulus (resistance to change in volume)[21].

TRAPPED VOLUME INSERTION GAIN MEASUREMENT

The influence of the difference in the mechanisms of power transmission into the ear between open ear (acoustic) conditions and sealed ear (pneumatic) conditions are illustrated by studies involving insert ear tips (ear buds) in a Zwislocki Coupler. In these tests, pure tones of various frequency were played through the ear tips. A small probe microphone (Knowles FG) was placed in the coupler to record sound pressure level SPL as it would exist in front of the ear drum. These measurements are made for the ear tip sealed in the coupler and then compared with measurements made under identical conditions except that the ear tip is not sealed in the coupler; the depth of insertion into the coupler, with and without a seal, is the same. Commercially available insert ear tips (Skullcandy) were used in this study. 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 3a 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 and midrange frequencies in the sealed over the unsealed case. Figure 3b plots the experimentally determined TVIG calculated by subtracting the curve in Figure 3a for the unsealed condition from that for the sealed condition. Also plotted in Figure 3b is the TVIG estimated by comparing the conversion of power from the speaker (operated at 1 mW) into pneumatic pressure vs. acoustic pressure. The fact that this power conversion model is so simple and includes no specific properties of the coupler or an ear, yet

captures the essence of the relationship indicates the importance of this concept in understanding the coupling of sound into the ear. For comparison to our experimental data in Figure 3, recently published data on a very similar experiment using insert headphones in a simulated ear canal, yielded very similar results.[22] This included showing that the gain effect is much larger at smaller trapped volumes than at larger trapped volumes, an observation which agrees with our relationship for pneumatic pressure in the trapped volume: $W/(Vv)$ where V is the trapped volume in the ear canal. As V gets smaller the pressure gain gets larger.

Using the same experimental setup as (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, displayed as phase angle of the pressure oscillations in the sealed condition relative to the open, are shown in Figure 4. If in the open condition pressure is assumed to be in phase with speaker and molecular motion, then in the sealed case the pressure lags motion (flow) by about 90°at low frequencies, as would be expected for an acoustic compliance. As frequency increases the relative importance of compliance and inertance shifts, being about equally balanced at about 200 Hz. At higher frequencies, the sealed pressure phase leading the flow (unsealed pressure) indicated higher relative importance of inertance effects.
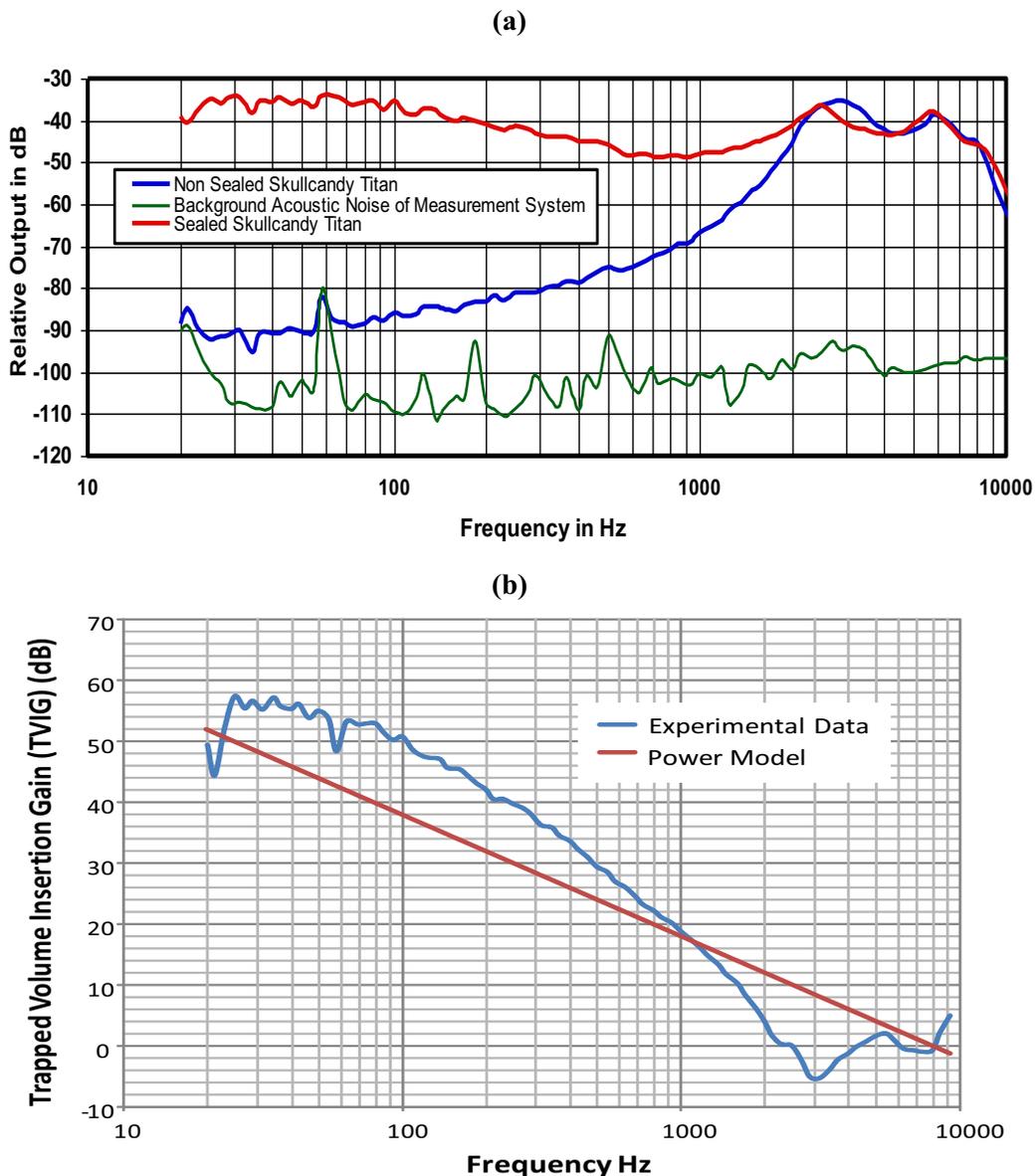
(a)

(b)

FIGURE 3: Measurement of TVIG. (a) Measurements of Unsealed and Sealed SPL, (b) TVIG Calculated From Measurement
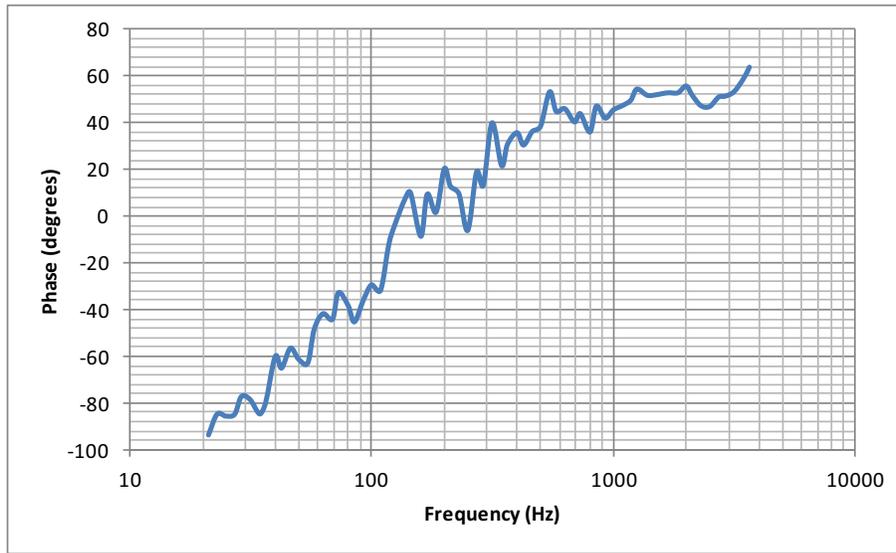
FIGURE 4: Phase Difference Between Sealed and Unseal Ear-Tip

## MITIGATIONS OF NEGATIVE EFFECTS OF SEALING A SPEAKER IN THE EAR

The large amplitude pneumatic pressure oscillations resulting when a speaker 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 hearing health. 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 at least partially allows acoustic rather than pneumatic sound behavior. One approach to achieving this is the use of an inflatable ear seal with a compliant surface.[23-25] 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 pneumatic 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. Figure 5 shows a commercial ear tip that has been modified to include 8 such pneumatically compliant membrane vents (PCMVs). The flexible membrane material covering the vents should be very light and flexible, and is typically a polymer material such as expanded polytetrfluoroethylene (ePTFE).

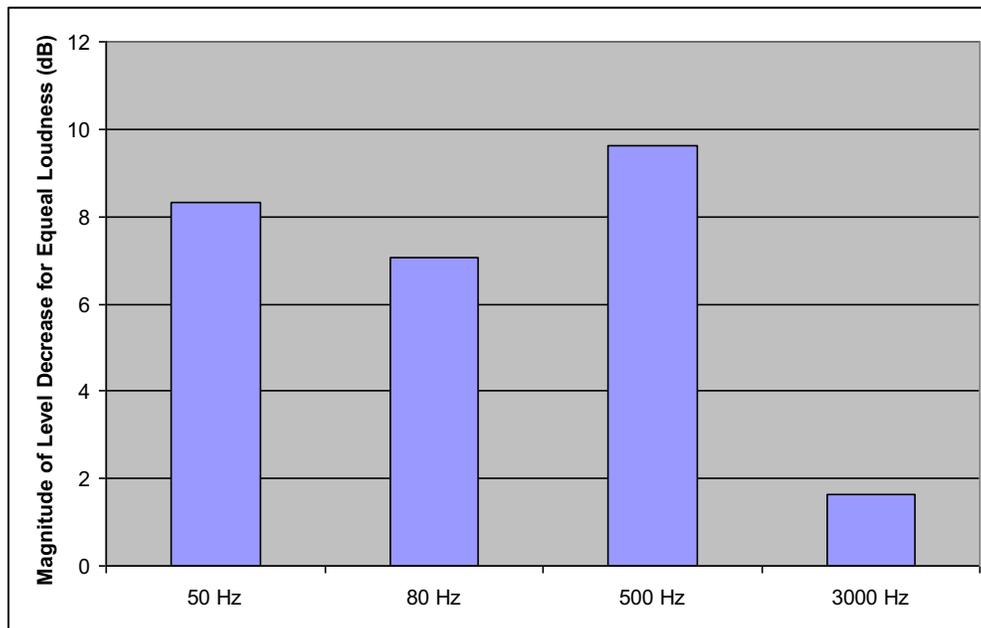**FIGURE 5:** Modified Ear Tip with pneumatically compliant membrane vents (PCMVs)

Figure 6 shows the results of testing on this ear tip with the PCMVs. It shows the relative SPL vs. frequency for the ear tip with the PCMVs as compared to the same type of ear tip without the PCMVs, 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 PCMVs reduces pneumatic 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 the PCMVs in the ear tip. This reduction in the trapped volume insertion gain has a strong likelihood of preventing the stapedius reflex and temporary threshold shift under normal listening conditions, and thereby preventing audio fatigue and potentially preventing long term hearing damage.
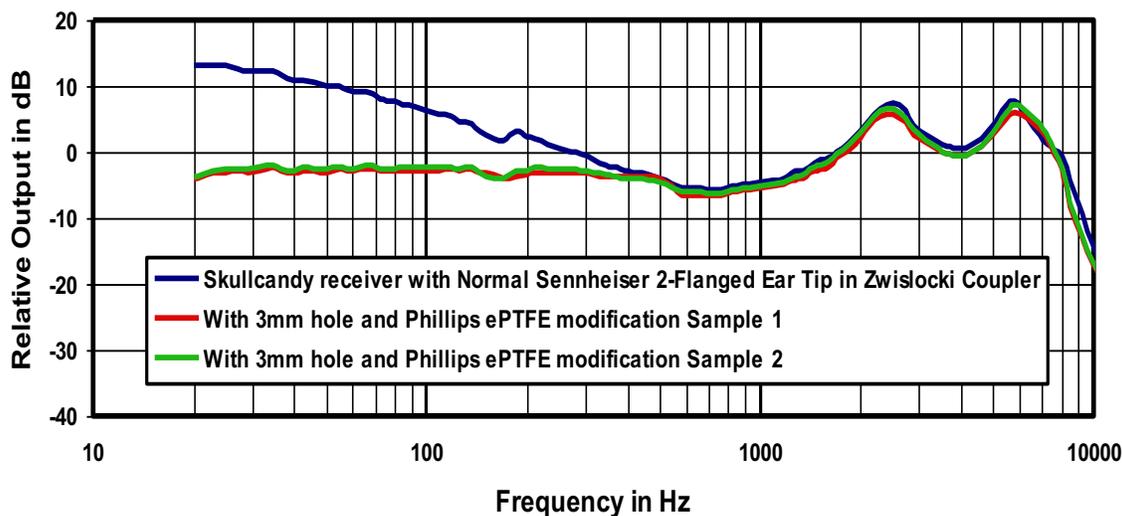
FIGURE 6: Comparison of SPL Levels in a Human Ear Canal when Sealed with a Conventional Ear Tip (blue), and an Ear Tip with pneumatically compliant membrane vents (green & red).

Listeners using ear tips with the PCMVs report a more three dimensional spatial awareness of the audio signal and seem to obtain the perception of their desired loudness at lower actual SPL. Figure 7 shows preliminary data in which listeners were asked to match the loudness of tones played in the PCMV modified ear buds to the standard ear buds, one in each ear. The tones were not played simultaneously but were alternated in quick succession. The figure

shows that there was a significant reduction in the SPL needed in the PCMV modified ear tip to achieve the same level of perceived loudness as the unmodified ear tip. This means that the recreational listener can satisfy their desire for loud music and wearer of a hearing aid fitted with PCMVs can obtain sufficient amplification with less SPL and thus less chance of audio fatigue and further hearing loss.

FIGURE 7: Decrease in SPL for same perceived loudness in modified ear tip with pneumatically compliant membrane vents (PCMVs) compared to unmodified ear tip.

ACKNOWLEDGMENTS

REFERENCES

1. 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.)
2. S. D. Ambrose "High Fidelity Earphone and Hearing Aid" U.S. Patent 4,852,177; July 24, 1989.
3. W. L. Creten and K. J. Van Camp. "Transient and Quasi-Static Tympanometry" *Scand Audiol* 3: 3942. 1974.
4. 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.
5. G. Liden, E. Harford, O. Hallen. "Automatic Tympanometry in Clinical Practice" *Audiology* 13: 126-139 (1974).
6. J.-E. Zakrisson, and E. Borg. "Stapedius Reflex and Auditory Fatigue" *Audiology* 13: 231-235 (1974).
7. U. Reker. "Normal Values of the Ipsilateral Acoustic Stapedius Reflex Threshold" Arch. Oto-Rhino-Laryng. 215, 25-34 (1977).
8. L. J. Deutsch."The Threshold of the Stepedius Reflex for Pure Tone and Noise Stimuli" *Acta Otolaryng* 74: 248-251, 1972
9. 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
10. C. A. Mangham, J. M. Miller. "A Case for Further Quantification of the Stapedius Reflex" *Arch Otolaryngol* Vol. 105, 593-596, 1979.

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

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

13. 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.

14. John H. Macrae. "An Investigation of Temporary Threshold Shift Caused by Hearing Aid Use" *Journal of Speech and Hearing Research*, Volume 37, 227-237, February 1994.

15. John H. Macrae. "Temporary Threshold Shift Caused by Hearing Aid Use" *Journal of Speech and Hearing Research,* Volume 36, 365-372, April 1993.

16. John H. Macrae. "Permanent Threshold Shift Associated With Overamplification by Hearing Aids" J*ournal of Speech and Hearing Research*, Volume 34, 403-414, April 1991.

17. John H. Macrae. "Prediction of Deterioration in Hearing due to Hearing Aid Use" *Journal of Speech and Hearing Research*, Volume 34, 661-670, June 1991.

18. John H. Macrae. "Prediction of Asymptotic Threshold Shift Caused by Hearing Aid Use" *Journal of Speech and Hearing Research*, Volume 37, 1450-1458, December 1994.

19. J.H. Macrae. "Presbycusis and noise-induced permanent threshold shift" *J. Acoust. Soc. Am.* 90 (5), 2513-2516, November1 991.

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

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

22. 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.

23. Stephen D. Ambrose, Samuel P. Gido, Jimmy W. Mays, Roland Weidisch, Robert Schulein. "Diaphonic Acoustic Transduction Coupler and Ear Bud." U. S. Patent 8,340,310 B2. Filed July 23, 2008, Granted Dec. 25, 2012.

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

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