MONITORING SOUND PRESSURE AT THE EARDRUM FOR HEARING CONSERVATION

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1. INTRODUCTION

It is well known that the sound pressure at the eardrum differs from that measured near the head, or in the absence of the subject. The differences arise from the interaction of structures forming the external ear, and the head and torso, with the sound field. Amplification of sound reaching the eardrum by the pinna occurs at frequencies above ~1kHz, and by the head and torso above ~200 Hz, depending on source characteristics (Brammer and Piercy, 1977). The relationship between the sound pressure at the eardrum and that of an external sound field is further modified, of course, by the use of hearing protectors.

The need to monitor sound pressures at the eardrum for the purposes of hearing conservation has long been recognized. A method for monitoring sound pressures within the ear was described by Brammer and Piercy, who for "practical considerations" mounted a small microphone on the base of the concha, and developed pressure transformations to estimate the sound pressure at the center-head position in the absence of the subject (Brammer and Piercy, 1977). The use of a probe microphone for noise dosimetry was described by Shotland, who inserted the probe tip a pre-determined distance into the ear canal (Shotland, 1996). No attempt was made to determine the pressure transformation to the eardrum. The probe microphone sensed sound pressures up to 4 kHz, and was held in place by a headband, which limited the use of hearing protection. An increase in exposure was observed compared to that recorded at the shoulder, or chest for all subjects. The increase depended on the individual and differed sufficiently between individuals (by up to 6 dB) to suggest external ear gain as a risk factor for noise-induced hearing loss.

In this paper, a probe microphone assembly is described that permits the uncertainty in probe-tip position to be eliminated, and hence the transfer function to the eardrum to be estimated. The microphone is attached to an ear mold designed to self-locate within the concha and ear canal, and so reproducibly position the probe tip. For the purposes of the present work, an upper frequency limit of 6 kHz was selected for the device, and a target accuracy of ±2 dB.

2. APPARATUS AND METHOD

The device consists of a miniature probe microphone and a custom-fitted ear mold. The ear mold is fabricated from an ear impression that is obtained for each subject following established audiological procedures. The ear impression provides the contour of the perimeter of the concha and cymba, which is required to produce the 'C'-shaped structure used to position the ear mold external to the ear canal. A third arm of the ear mold rests along the upper surface of the ear canal, and contains a hole through which the probe tube is inserted, as can be seen from Fig. 1.

The probe microphone is constructed from a miniature electret microphone (Knowles FG 23652), to which is attached a 35 mm soft silicone tube, with outer diameter of 0.94 mm. This assembly has a Helmholz resonance frequency ~1.5 kHz, as well as probe tube length resonances that commence at ~4.5 kHz. The overall response is digitally equalized to within ±1 dB at frequencies up to 6 kHz (and with somewhat less precision up to 12 kHz). The output of the probe microphone is amplified by a custom-designed, low-noise preamplifier with a flat frequency response from 20 Hz to 17 kHz, and voltage gain of 34 dB.

The device is assembled after first locating the ear mold in the external ear, and then feeding the probe through the hole in its supporting tube. For this procedure, the subject is seated in an anechoic chamber with a sound source on the inter-aural axis, 1.5 m from the ear. The loudspeaker output was flat (on axis) to within ±2 dB from 100 Hz to 14 kHz (PSB Image 2B). The tip of the probe tube is adjusted by observing the minimum frequency of the standing wave pattern at different probe locations in the ear canal (Gilman and Dirks, 1986, Stinson, 1990). A frequency of 11 kHz was selected for the target standing wave minimum, and corresponded to the smallest separation between probe tip and eardrum considered safely achievable for all subjects, male and female, irrespective of the length of the ear canal. The microphone assembly is glued to the ear mold when the desired frequency was obtained.

All subjects gave their informed consent to participate in the study, following the provisions of the ethics committee of the University of Connecticut Health Center.

3. RESULTS AND DISCUSSION

3.1 Standing Wave Minima in Ear Canal

The microphone output for three penetration depths of the probe tip in a subject's ear canal are shown in Fig. 2. Inspection of the diagram reveals features that have been observed in measurements conducted on all subjects.

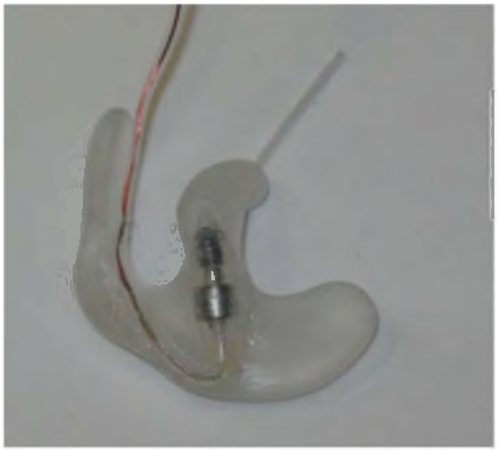

Figure 1. Photograph of probe microphone and ear mold

At frequencies below about 2 kHz, the three spectra are indistinguishable from each other, indicating that the sound pressure within the ear canal is insensitive to the position of the probe tip at these frequencies, as expected (Gilman and Dirks, 1986). All spectra contain common features at some other frequencies, namely a maximum between 2.5 and 3 kHz, and a large minimum between 6.5 and 8.5 kHz. These reflect specific features of the head-related transfer function and are not believed to be associated with the standing wave pattern in the ear canal, which would tend to introduce differences between the spectra. When the common features of the spectra are discounted, three minima at frequencies of approximately 6, 8.8 and 11 kHz can be distinguished, corresponding to the different penetration depths of the probe tip. The resolution of the minimum at 8.8 kHz is poorly defined in Fig. 2, possibly because it overlaps with the dominant feature of the head related transfer function between 6.5 and 8.5 kHz.

3.2 Sources of Error

Variation in position of probe tip on repeated insertion

The variability in the position of the probe tip on repeated insertion in the ear canal is difficult to measure directly, particularly when the probe tip is close to the eardrum. However, a change in penetration depth of the probe tip, and hence position relative to the eardrum, will result in a change in the standing wave pattern. Accordingly, the frequency of the standing wave minimum has been recorded for repeated placement of the ear mold in the ear. For six such repetitions, the lowest to highest minimum frequency ranged from 2% to 4% for different ears. Reference to Fig. 2 reveals that a 20% reduction in standing wave minimum frequency (i.e., from 11 kHz to 8.8 kHz) will introduce a change in microphone output of a maximum of ~4 dB at 6 kHz, and less at lower frequencies. A variation of 2% to 4% will therefore introduce a negligible change in microphone output (<0.5 dB).

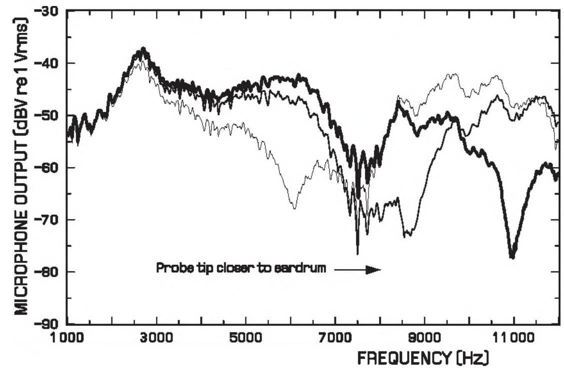

Figure 2. Microphone output for three positions of the probe tip

Influence of probe on sound pressure in ear canal

The perturbation of the sound field by the presence of the ear mold has been evaluated by inserting a second probe microphone with a long, small diameter, probe tube into the ear canal (Etymotic ER-7C). A systematic variation in sound pressure level (SPL) with frequency has been found when the ear mold is first present and then removed, which appears to depend somewhat on the physical dimensions of the external ear. Compensation for this effect appears possible within the error budget of ±2 dB.

Eardrum impedance

Although the probe tip is positioned close to the eardrum, it is desirable to reconstruct the SPL at the eardrum. Such estimates will be influenced by differences in eardrum impedance. If typical energy reflection coefficients for human ears are employed (Stinson, 1990), the predicted SPLs at the eardrum differ systematically from the measured SPLs by 3.6 dB at 6 kHz, and progressively less at lower frequencies. While the maximum variation in the energy reflection coefficients between ears will introduce an error in the transformed SPLs of <0.5 dB, the error arising from differences in the phase of the eardrum impedance between ears is less certain. Gilman and Dirks estimated a total variation from eardrum impedance of close to 2 dB for a standing wave minimum at 8 kHz. It remains a subject for future work to confirm that the phase error of the transformation remains within the error budget.

REFERENCES

Brammer, A. J., and Piercy, J. E. (1977). Monitoring sound pressures within the ear: Application to noise exposure. J. Acoust. Soc. Am. **61**, 731-738.

Gilman, S., and Dirks, D. D. (1986). Acoustics of ear canal measurement of eardrum SPL in simulators. J. Acoust. Soc. Am. **80**, 783-793.

Stinson, M. R. (1990). Revision of estimates of acoustic energy reflectance at the human eardrum. J. Acoust. Soc. Am. **88**, 1773-1778.

Shotland, L. I. (1996). Dosimetry measurements using a probe tube microphone in the ear canal. J. Acoust. Soc. Am. **99**, 979-984.

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