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# A New Method to Estimate Sound Energy Entering the Middle Ear

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***Abstract*—Standing waves in the ear canal can cause inaccurate quantification of the sound pressure level (SPL) entering the ear and therefore lead to unreliable results in clinical tests. Since it is impractical to directly measure the SPL at the eardrum position, in this study we proposed a new method to estimate the eardrum SPL by solely making measurement at the entry of the ear canal. To achieve this, the acoustic characteristics of the earphone were calculated using a calculation tube with variable lengths. Then the ear canal impedance was calculated according to the obtained source characteristics. Finally, the eardrum SPL was estimated by the ear-canal impedance and the SPL measured at the entry of the ear canal. The results showed that the eardrum SPL could be reliably estimated for all the five subjects participated in this study. The maximal estimation error was less than 3 dB for all frequencies from 0.5 to 10 kHz. These findings suggested that the proposed method could avoid the standing wave problem and therefore might be a great candidate for accurate calibration of sound pressure in various acoustic measurements.**

## I. Introduction

The ear canal can be considered as a tube with one end open to the air and the other end terminated by the eardrum. When the sound travels along the ear canal and hits the eardrum, part of the sound energy is reflected by the eardrum and then travels backward in a reversed direction. The forward and backward sound waves can enhance or cancel each other dependent on their phase relation, resulting in a standing wave in the in the ear canal. When the forward and backward waves are in phase, they can enhance each other and a pressure maximum can be present; by contrast, a pressure minimum (or null) will be observed when the two components are out of phase and cancel each other [1-3].

The standing wave has two aspects of impacts on the sound pressure measured in the ear canal: 1) when a complex sound with a flat amplitude spectrum is present to the ear canal, the sound pressure level (SPL) measured at the same position is no longer flat, due to the fact that the phase relations of the two components are different for different frequencies when the backward wave arrives [2]; 2) the SPL measured at different positions along the ear canal can be very different, for example, the SPL measured at the entry of the ear canal cannot be used to represent the SPL at the eardrum, given that the eardrum SPL is commonly used as a reference of the sound energy entering the middle ear [4].

The standing wave can cause problems in acoustic measurements in human ears. For the standard audiogram test in the clinic, the threshold values may not be as reliable since it only specifies the sound level output by the headphones, without actually measuring the sound energy entering the middle ear [5]. For hearing aid fittings, the existence of standing waves can bring about the risk of over amplification over certain frequencies, which can cause discomfort and lead to performance degradation [6, 7]. For the measurements of otoacoustic emissions, the standing wave can cause great difficulty to the calibration of the stimulus levels and therefore reduce the accuracy of the results [8-11].

Various attempts have been made to solve the standing wave problem in ear-canal measurements. Many clinical practices simply use the SPL measured at the entry of the ear as the reference of the sound entering the middle ear. Such approach can introduce errors since the pressure at the entry may be quite different from the SPL at the eardrum [1, 8, 12]. Some investigators tried to measure the eardrum SPL with a microphone placed within a few millimeters from the eardrum [1, 10]. However, inserting a microphone so close could cause discomfort and introduce potential threat of damaging the eardrum. Another solution is to model the ear canal as a uniform tube [3]. However, there is no guarantee that the acoustic characteristics of the uniform tubes are exactly the same as the real ear, given that large individual differences exist in the ear-canal acoustics.

The purpose of this study was to propose a new method of estimating the SPL at the eardrum without the need of inserting any microphones deep into the ear canal. The method used an acoustic transmission line model to estimate the eardrum SPL by simply measuring the SPL at the entry of the ear canal. The estimated eardrum SPL was then verified by comparing it with the result of the real-ear measurement.

## II. Method

### *A. Materials and Subjects*

A calculation tube was used for the estimation of the SPL at the eardrum (Figure 1). The tube was composed of a plastic tube with both ends open and a rubber piston which was inserted into the tube. The piston terminated one end of the tube without leakage and could move freely inside. A foam eartip containing an earphone and a microphone was inserted into the other end of the calculation tube to deliver acoustic stimulus and record the response. The inner diameter of the tube was 7 mm.

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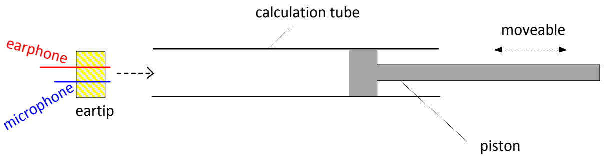


Figure 1. The calculation tube for the estimation of the SPL at the eardrum.

Five subjects with ages ranging from 24 to 43 years old were recruited in the real-ear measurement for the verification of the eardrum SPL estimation. The subjects had normal shape of ear canals and no history of outer ear surgery was reported. The protocols were approved by the Institutional Review Board (IRB) of Arizona State University, USA.

### B. Equipment

A custom program was developed in Labview (National Instruments, NI) to generate a wideband signal to a PXI-4461 data acquisition (DAQ) card (NI), where the signal was converted into analog voltages to drive an ER-2A earphone (Etymotic Research). The earphone was coupled with an ER-10B+ microphone inside a foam eartip. The acoustic response was recorded by the microphone and digitized at the DAQ card at a sampling rate of 48000 kS / s.

### C. Procedures

The estimate of the SPL at the eardrum was implemented by the following two steps. For each step, all measurements were repeated 10 times and the averaged signals over the 10 recordings were used to improve the signal to noise ratio. All variables expressed in capital letters below were functions of frequency.

#### 1) Calculation of source characteristics

The acoustic characteristics of the source (the ER-2A earphone) include the source pressure ($P_s$) and source impedance ($Z_s$), both expressed as amplitude and phase as functions of frequency. The study used a multiple-cavity approach similar to Allen's [13], in which the sound delivery system (Figure 1) was treated as an acoustic transmission line model in Figure 2.

To calculate $P_s$ and $Z_s$, the earphone was inserted into the calculation tube and played a chirp tone with its frequency increasing linearly from 0.5 to 10 kHz within 1 s. The level of the chirp tone was 60 dB SPL. The theoretical impedance of the calculation tube $Z_0$ can be calculated from the effective tube length (from the eartip to the piston) [14]. The corresponding acoustic responses ($P_i$) were measured at the eartip position. Then both $Z_0$ and $P_i$ were used to solve for $P_s$ and $Z_s$ with the following equation [13]:

$$\frac{P_s}{Z_s + Z_0} = \frac{P_i}{Z_0} \qquad (1)$$

A minimum of two $Z_0$'s were needed to solve for two unknown variables ($P_s$ and $Z_s$) and using more than two $Z_0$'s could help to improve the accuracy of the solution [14]. In this study, five effective tube lengths (1.0, 2.0, 3.0, 4.0 and 5.0 cm) were used to solve for optimized $P_s$ and $Z_s$ with a least mean square routine.

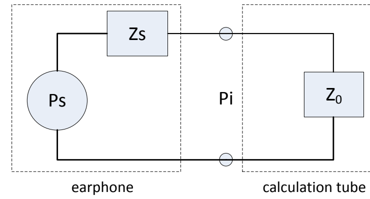


Figure 2. The acoustic transmission line model to calculate the source pressure ($P_s$) and source impedance ($Z_s$) of the earphone.

#### 2) Calculation of forward SPL

The same eartip was then inserted to the ear canal of each subject and played the same chirp stimulus. After the SPL at the entry of the ear canal ($P_L$) was measured, the ear-canal impedance ($Z_L$) could be calculated as:

$$Z_L = \frac{Z_s P_L}{P_s - P_L} \qquad (2)$$

Then the forward pressure ($P_+$), one of the two components forming the standing wave, could be obtained as:

$$P_+ = \frac{1}{2} P_L \left(1 + \frac{\rho c}{Z_L}\right) \qquad (3)$$

where $\rho$ is the air density and $c$ is the sound speed in the air. Finally, the amplitude of the estimated SPL at the eardrum ($P_E$') was twice the amplitude of the forward pressure:

$$|P_E'| = 2|P_+| \qquad (4)$$

After the SPL at the eardrum ($P_E$') was estimated by the above two steps, it was then compared with the actual pressure ($P_E$) measured by a second microphone (Figure 3). A soft silicon tube was attached to the second microphone and inserted within 2 mm to the eardrum. The insertion process was monitored by otoscopic visualization and would not cause discomfort of the subjects.

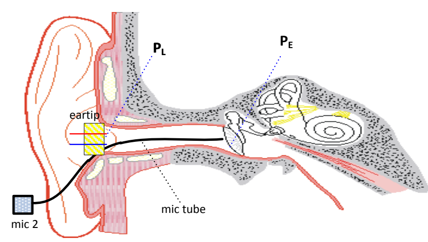


Figure 3. The experimental setup to verify the estimated sound pressure at the eardrum.

### D. Data analysis

In the calculation of source characteristics, the sound pressures Pi's were fast Fourier transformed into complex numbers in the frequency domain. The theoretical impedance $Z_0$'s (expressed in the frequency domain) were also calculated from the effective tube length. Each effective tube length corresponded to one single equation (1), and five equations of five tube lengths were put together to solve for $P_s$ and $Z_s$ via the rule of least mean squares. The solution was performed frequency by frequency from 0.5 kHz to 10 kHz with a frequency increment of 1 Hz.

After the $P_s$ and $Z_s$ were obtained, the impedance of the ear canal, the forward SPL and the estimated eardrum SPL were calculated successively in the frequency domain. Then the amplitude spectrum of the estimated eardrum SPL was compared with the actual sound pressure measured by the second microphone placed closed to the eardrum.

## III. Results

The calculation of source characteristics ($P_s$ and $Z_s$) is the most important step during the estimation of the eardrum SPL. The solutions were obtained by measuring wideband responses of several acoustic loads with known impedance. The calculation tube had a piston movable inside so as to provide as many known acoustic loads as needed. Figure 4 showed the amplitude and phase spectra of the $P_s$ and $Z_s$ solved by five effective lengths of the calculation tube: 1.0, 2.0, 3.0, 4.0 and 5.0 cm. It was observed from the figure that the amplitude of both $P_s$ and $Z_s$ were not constant across frequencies, i.e., the output power and acoustic impedance were higher for lower frequencies. The phases of $P_s$ and $Z_s$ fluctuated around 0 but never exceeded 2 rad as the frequency increased.

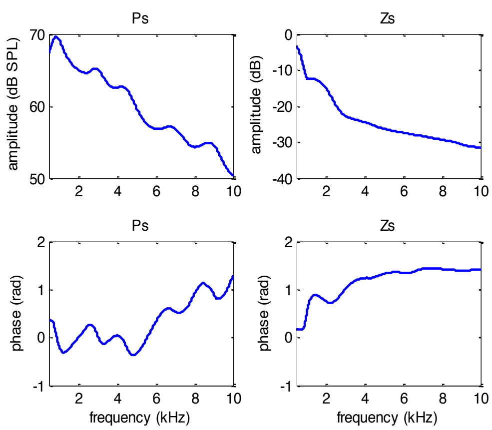


Figure 4. The amplitude and phase spectra of the two source characteristics ($P_s$ and $Z_s$).

Then the source characteristics in Figure 4 were used to calculate the impedance of a testing tube [with the effective length not previously used (3.4 cm)] using equation (2), to verify the accuracy of the obtained $P_s$ and $Z_s$. The calculated tube impedance, as well as the theoretical values by [14], was shown in Figure 5. It was observed that both the amplitude and phase matched well between the calculated and theoretical results. It was only at the deep peaks or notches that they showed slight deviations.

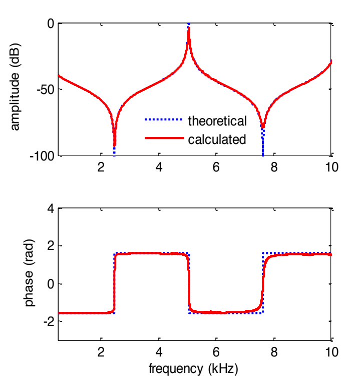


Figure 5. The comparison of the theoretical and calculated tube impedance.

After the accuracy of the obtained $P_s$ and $Z_s$ had been verified, they were used to estimate the eardrum SPL ($P_E$'). Meanwhile, the actual eardrum SPL ($P_E$) was also measured by a second microphone. An example (from subject # 2) of $P_E$ and $P_E$', as well as the SPL measure at the entry of the ear canal ($P_L$), was shown in Figure 6. The most important finding was that the estimated $P_E$' matched closely with the actual pressure $P_E$ across the whole frequency range. The maximal difference between $P_E$' and $P_E$ was about 3 dB. The estimation was best at the frequency where the amplitude showed a peak. On the other hand, it could be observed that there were very deep notches at around 3 kHz and 9 kHz for $P_L$, while such notches were completely absent for the SPL at the eardrum ($P_E$ or $P_E$'). Moreover, a peak was present around 6 kHz for all sound pressures.

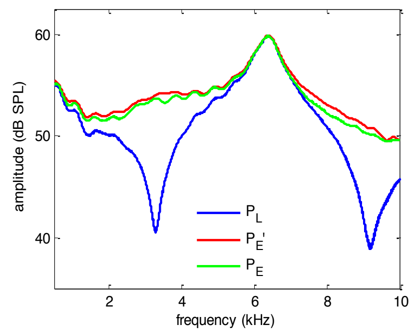


Figure 6. The comparison of the SPL at the entry of the ear canal ($P_L$), the estimated eardrum SPL ($P_E$') and the actual SPL measured at the eardrum ($P_E$). (Subject # 2)

## IV. Discussion

A multiple-cavity approach was proposed in this study to estimate the sound pressure level at the eardrum position, in order to accurately quantify the sound energy entering the middle ear.

### A. *Effects of standing waves*

In this study, significant effects of the standing wave on the ear-canal sound pressures were found (Figure 6): while the SPL at the entry of the ear canal ($P_L$) demonstrated deep notches, the eardrum SPL ($P_E$) was relatively flat around these frequencies. Such deep notches of $P_L$ were caused by cancellations of forward and backward pressures at certain frequencies where the two components were out of phase [1, 9, 15, 16]. The notch frequencies are dependent on the effective length of the ear canal $L$ (from the eartip to the eardrum) and they can be calculated by $f = nc/4L$ ($c$: speed of sound in the air; $n = 1,3,5,7\cdots$) according to the quarter wavelength theory. On the other hand, both $P_L$ and $P_E$ showed a peak at around 6 kHz. This is because the forward and backward sound pressures are in phase and enhance each other at such frequency. The peak frequency corresponds to the half wavelength of the ear canal.

### B. *Calculation of source characteristics*

The calculation of source characteristics ($P_s$ and $Z_s$) is a fundamental step when estimating the eardrum SPL. The accuracy can be affected by many factors, such as the number of the tube lengths selected, the diameter of the calculation tube and the frequency response of the earphone [13].

Theoretically, two tube lengths should be sufficient since only two unknown variables need to be solved. However, the solutions may be inaccurate around the notch frequency of either $P_i$ where the sound pressure measurement is easily contaminated by background noises. Increasing the number of different tube lengths can overcome this problem. Studies recommend that four to six tube lengths are enough [14, 17], and we used five lengths for the solution. Regarding to the tube diameter, we used a calculation tube with a diameter close to the averaged diameter of adult ear canals, so that the source characteristics remained the same after switching from the tube to the ear canal. For the obtained source characteristics in this study (Figure 4), the output sound pressure is lower for higher frequencies, although the driving stimulus has a flat spectrum. Such frequency difference is determined by the frequency response of the earphone whose output power is limited for high frequencies.

### C. *Estimation of eardrum SPL*

A key finding of this study is that the SPL at the eardrum position could be reliably estimated by measuring the SPL at the entry of the ear canal (Figure 6). The mean estimate error, which was calculated by the absolute difference between $P_E$' and $P_E$ averaged across frequencies from 0.5 to 10 kHz, was less than 3 dB for all the 5 subjects. Such estimate error of sound levels is acceptable for nearly all hearing testing [18, 19]. The estimation was best at the peak frequencies and the error slightly increased around the notches frequencies of $P_L$. The explanation is that the eardrum SPL ($P_E$') was calculated from the $P_L$ measured at the entry of the ear canal, and the $P_L$ was more vulnerable to background noises around the notch frequencies, leading to declined performance of the $P_E$' estimation . This is different from other similar methods where the forward sound pressure is predicted [11, 15, 17, 20, 21]. Although the forward pressure is also not affected by the standing wave, it cannot be actually measured anywhere in the ear. Estimating the eardrum SPL in the present study permits the assessment of the validity. Another advantage of estimating the eardrum pressure is that it does not require a direct measurement near the eardrum position. Although direct measurement is an ideal way to obtain the actual pressure at the eardrum [1, 10], deep insertion of a probe microphone could lead to discomfort of the subjects, especially for young children who may not be able to tolerate the approach. The direct measurement of $P_E$ in this study was only for the validation purpose.

## V. Conclusion

This study showed that the standing wave can cause serious problems in quantifying the SPL entering the ear. This study proposed an alternative to direct measurement of eardrum SPL. The proposed method is capable of estimating the eardrum SPL by painless measurements at the entry of the ear canal. The great reliability of the estimation suggests that the method may be a great candidate for accurate sound pressure calibration in different situations, such as the audiogram tests, the hearing aid fittings and otoacoustic emission measurements.


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