Influence of the Depth of Human Ear Canal on Sound Pressure Distribution

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Received 20 Jan 2010; Accepted 1 Jul 2010; doi: 10.5405/jmbe.754

Abstract

This study was to measure the sound pressure distribution by examining the ear canal resonance in the human ear canals. The mean gain for various stimulus frequencies was analyzed at four different measuring points. A comparative evaluation showed that the mean gain for different stimulus frequencies at a depth of 2.0 cm was consistent with the results of Dillon’s study. In addition, it found that the mean gain at a stimulus frequency of 4000 Hz was affected by the interior shape of the ear canal, particularly at the depths of 0.5 cm and 1.0 cm, while mean gain was only affected by the length of the ear canal for the stimulus frequency of 2000 Hz. The findings of this study may have potential clinical applications for the selection and fitting of in-the-canal and completely-in-the-canal hearing aids, as well as for canalplasty and congenital aural atresia surgery.

Keywords: Sound pressure, External auditory canal, Ear canal resonance, Real ear measurement

1. Introduction

The ear canal, or external auditory canal (EAC), has a mean length in adults of 22.5 mm [1]. The EAC consists of an outer cartilaginous portion, in which the first and second ear canal bends are located, and an inner bony portion that runs through the temporal bone and terminates at the tympanic membrane (TM). The EAC plays an important role in sound transmission by amplifying incoming sounds at certain frequencies. Despite this important role, the shape of the ear canal is not uniform, and the influence of the depth of the human ear canal on sound pressure distribution has not been given sufficient attention in the literature.

For the purposes of analyzing the sound pressure transmission [2], it is convenient to consider the ear canal as a uniform cylindrical tube of length L and diameter d. Sound pressure variations along the ear canal length L can become significant when the sound wavelength (λ) is < 10 L.

Variations in the ear canal diameter d can become significant with changes in ear canal cross-section or mechanical properties, such as near the TM [3]. The first mode that creates these transverse variations can propagate along the ear canal at frequencies where λ < d/0.59 [4,5]. The ear canal is not a uniform tube, however, and its noncircular nature lowers the frequency at which spatial variations can influence sound pressure in the EAC.

Three approaches have been used to measure the outer ear transfer function. One approach uses a mathematical model of the ear canal [6,7] to estimate the sound pressure at the TM. The second approach is to calibrate the earphone output in an “artificial ear” that mimics the essential dimensions of the ear canal. This approach has also been used to calibrate audiometric earphones [8]. Ravicz et al. [12] have shown that an artificial ear technique might underestimate the in situ sound pressure by 5 to 15 dB between 40 and 60 kHz. The third most common approach [1,9] utilizes real ear measurement (REM) by means of a probe-tube microphone to measure sound pressure at a point near the TM. In the clinical context, REM is more commonly used to record resonance measurements close to the tympanic membrane rather than to map the distribution

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of sound pressures and resonance within the ear canal, and it does not measure resonance at other depths within the EAC.

However, there is few research focusing on the influence of the depth of human ear canal on mean sound pressure distribution. The purpose of this study was thus to measure the sound pressure variations at different depths within the human ear canal. By using REM, this study analyzed the influence of depth on the mean sound pressure distribution within the canal at different frequencies. A better understanding of mean sound pressure distribution and its importance to hearing may have potential applications for hearing aid placement and canalplasty procedures.

2. Materials and methods

2.1 Subject preparation

There were 18 participants (36 ears) aged between 20 and 30 years (11 males/seven females), all of whom had normal hearing and middle ears. None of the subjects reported hearing-related medical conditions. All subjects had normal hearing sensitivity with pure-tone thresholds better than 15 dB HL at audiometric test frequencies, as measured by the pure tone audiometer (RION AUDIOMETER AA-72B). Subjects were required to have normal middle ear function as assessed by tympanometry (defined as middle ear pressure +50 to -50 daPa and middle ear compliance +0.3 to +1.5 mmho, with a probe tone frequency of 226 Hz as measured using an impedance audiometer, RION IMPEDANCE AUDIOMETER RS-21). This prospective study was approved by the Institutional Review Board of Chang Gung Memorial Hospital. Written informed consent was obtained from all subjects enrolled in the study.

2.2 Stimulus generation and depths of gain measurement

This study assumed that the height of subjects, the location of instruments, and the background noise would not affect the measured results. The experiment was performed in a sound booth, and the speakers were adjusted according to the subject’s height for REM. The sweep tone was used in this study. Stimulus intensities was 60 dB SPL based on the normal spoken sound pressure, with frequencies of 500, 1000, 2000, 4000 Hz based on the standard clinical hearing test. Measurements were taken progressively closer to the tympanic membrane, at depths of 0.5, 1.0, 1.5 and 2.0 cm from the entrance to the ear canal. Note that the depth of 2.0 cm was closest to the tympanic membrane.

2.3 Procedure for detecting sound intensity distribution

A real ear measurement system (MAICO RM500), probe tube, pure tone audiometer and impedance audiometer were used for this study. The procedure of the experiment was as follows. (1) The pure tone audiometer was used to determine the pure tone threshold of the subjects. (2) The impedance audiometer was used to examine the middle ear function of the subjects. (3) The real ear measurement was performed using the MAICO RM500 system. (4) The sound source was placed at a distance of 30 cm in front of the subject’s head, at 45 degrees azimuth. (5) The probe tube, shown in Fig. 1(a), was laid along the floor of the EAC. The measured depths within the EAC were 0.5, 1.0, 1.5 and 2.0 cm, as measured from the entrance of the canal shown in Fig. 1(b). Thirty-six ear canals were measured at stimulus frequencies of 500, 1000, 2000, and 4000 Hz. Mean gain distributions within the EACs were then determined by comparing the sound pressure in the EAC at each of the different stimulus frequencies with that obtained by the reference microphone shown in Fig. (c).

Figure 1. The (a) probe tube was laid along the floor of the ear canal. The depths were measured from the (b) entrance of the canal. The (c) reference microphone was placed on the pinna.

3. Results

Mean sound pressure in the external auditory canal at a stimulus intensity of 60 dB SPL is shown in Table 1. After comparing the sound pressure in the EAC at each of the different stimulus frequencies with that obtained by the reference microphone, the mean gain in the EAC at a stimulus intensity of 60 dB SPL was derived, as shown in Table 2. Note that it was determined by averaging the gain for stimulus frequencies at 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz.

At a depth of 2.0 cm, there was minimal gain at both 500 Hz or 1000 Hz. At 2000 Hz, however, the mean gain was 12.5 dB, while at 4000 Hz, the mean gain was 15 dB.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>59.25</td>
<td>59.05</td>
<td>70.00</td>
<td>65.00</td>
</tr>
<tr>
<td>1</td>
<td>59.20</td>
<td>58.70</td>
<td>71.00</td>
<td>68.00</td>
</tr>
<tr>
<td>1.5</td>
<td>59.35</td>
<td>59.40</td>
<td>72.50</td>
<td>71.50</td>
</tr>
<tr>
<td>2</td>
<td>59.10</td>
<td>59.95</td>
<td>72.50</td>
<td>75.00</td>
</tr>
</tbody>
</table>

Table 1. Mean sound pressure in the external auditory canal at a stimulus intensity of 60 dB SPL (unit: dB SPL).
Table 2. Mean Gain in the external auditory canal at a stimulus intensity of 60 dB SPL (unit: dB).

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>4000 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>-0.75</td>
<td>-0.95</td>
<td>10.00</td>
<td>5.00</td>
</tr>
<tr>
<td>1</td>
<td>-0.80</td>
<td>-1.30</td>
<td>11.00</td>
<td>8.00</td>
</tr>
<tr>
<td>1.5</td>
<td>-0.65</td>
<td>-0.60</td>
<td>12.50</td>
<td>11.50</td>
</tr>
<tr>
<td>2</td>
<td>-0.90</td>
<td>-0.05</td>
<td>12.50</td>
<td>15.00</td>
</tr>
<tr>
<td>Dillon, 2001</td>
<td>2.00</td>
<td>3.00</td>
<td>12.00</td>
<td>14.00</td>
</tr>
</tbody>
</table>

These results indicated that at a depth of 2.0 cm, maximum gain was obtained at 4000 Hz, and this is consistent with the findings in Dillon [10]. At a depth of 1.5 cm, there was minimal gain obtained at both 500 Hz or 1000 Hz. At 2000 Hz, the mean gain was 12.5 dB, and that at 4000 Hz was 11.5 dB. The mean gain at 2000 Hz was thus greater than the mean gain at 4000 Hz. At a depth of 1.0 cm, there was again minimal gain at 500 Hz and 1000 Hz. At 2000 Hz, the mean gain was 11.00 dB, and the mean gain at 4000 Hz was 8.00 dB. At this point within the EAC, the mean gain at 2000 Hz was greater than that at 4000 Hz. A depth of 0.5 cm, there was minimal gain at 500 Hz and 1000 Hz. At 2000 Hz, the mean gain was 10.00 dB, and that at 4000 Hz was 5.00 dB. As was the case for the depths of 1.5 cm and 1.0 cm, the mean gain at 2000 Hz was greater at 4000 Hz.

In Fig. 2, the solid line with the symbol of “○” is used to represent data derived from a depth of 2.0 cm from the entrance of the ear canal, which was the closest measuring point to the TM. The □, ▽, and ◊ symbols represent data obtained from depths of 1.5 cm, 1.0 cm, and 0.5 cm from the ear canal entrance, respectively. The points on the graph joined by the dashed line represent data from a previous study by Dillon [10], and are shown only for the depth closest to the TM. At a depth of 2.0 cm, mean gain measured at this depth was consistent with the findings in Dillon [10] for all stimulus frequencies, although this earlier study only looked at the gain close to the tympanic membrane. In contrast, this study has further demonstrated that mean gain is affected by different depths (0.5 cm, 1.0 cm, 1.5 cm) within the EAC.

The EAC plays an important role in sound transmission by amplifying incoming sounds at certain frequencies. Although the ear canal is not like a uniform tube, the influence of the depth of the human ear canal on sound pressure distribution has not been given sufficient attention in the literature.

The mean gain in the ear canal is shown in Fig. 3. There was minimal gain caused by ear canal resonance at stimulus frequencies of 500 Hz and 1000 Hz. Sound pressure variations along the ear canal length (L) can exist at frequencies where the wavelength of the sound (λ) is less than 10 L [2]. Stimulus frequencies of 500 Hz and 1000 Hz, however, have a wavelength greater than 10 L. Consequently, standing waves of such frequency create no resonance at any depth within the ear canal. This possibly explains why resonance gain was not observed at stimulus frequencies of 500 Hz and 1000 Hz, but was seen at 2000 Hz and 4000 Hz.

At 2000 Hz, resonance gain was observed because the wavelength of the stimuli was less than 10 L. This study also found that there was no variation between the four measuring points. While Rabbitt et al. [3] found that sound pressure varies across the ear canal diameter (d) at high frequencies, they did not quantify these frequencies. However, a substantial difference in mean gain was seen among the four measuring points at 4000 Hz in Fig. 3, and our results demonstrated that the EAC depths of 0.5 cm, 1.0 cm and 1.5 cm affect the mean gain at frequencies of 4000 Hz.

Since the ear canal is a curved, rather than a straight, tubular structure, its diameter is different at depths of 0.5 cm and 1.0 cm. These variations in EAC diameter affect the mean gain at frequencies of 4000 Hz. This may explain why the gain variation between measuring points at 4000 Hz was more affected than at other frequencies. Furthermore, the mean gain at 4000 Hz was greater at the depth of 1.0 cm than at 0.5 cm. This study has shown that gain varies depending on the point where it is measured. Recognition of gain distribution at the depths of 0.5 cm, 1.0 cm and 1.5 cm may have clinical applications for the selection and fitting of in-the-canal (ITC) and completely-in-the-canal (CIC) hearing aids, as well as for canalplasty and congenital aural atresia surgery.

5. Conclusions

This study measured the sound pressure distribution by examining the ear canal resonance in the human ear canals. The
mean gain for various stimulus frequencies was analyzed at four different measuring points. A comparative evaluation showed that the mean gain for different stimulus frequencies at a depth of 2.0 cm was consistent with the results of Dillon’s study [10]. This study also found that there was minimal gain at stimulus frequencies of 500 Hz and 1000 Hz, regardless of the depth of measurement. In addition, it found that the mean gain at a stimulus frequency of 4000 Hz was affected by the interior shape of the EAC, particularly at the depths of 0.5 cm and 1.0 cm, while mean gain was only affected by the length of the EAC for stimulus frequencies of 2000 Hz.

The findings of this study may have potential clinical applications in canalplasty and congenital aural atresia (CAA) surgery, and may be used to guide surgeries that attempt to reshape the EAC to achieve more desirable hearing outcomes. Since the surgical management of such procedures requires knowledge about not only the depth of ear canal but also the width and shape, subsequent research will focus on these last two factors as well as the length of sound waves.

Acknowledgements

Support for this project was provided by the National Science Council (NSC 99-2628-E-182-001) and Chang Gung Memorial Hospital (CMRPD260053). Facilities were provided by the Biomedical Engineering Center in Chang Gung University.

References