Attenuation as a function of the canal length of custom-molded earplugs: A pilot study

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Abstract: Custom-molded earplugs (CMEPs) whose canal segments extend beyond the second bend of the ear canal can provide excellent attenuation but can sometimes be uncomfortable. Attenuation was measured for CMEPs whose canal segments were shortened in 2-mm increments. The within-subjects design permitted illustration of the form of the function relating attenuation to canal segment length for individuals. Reduction of attenuation due to canal segment shortening was generally more pronounced for frequencies \( \leq 1000 \text{ Hz} \). Some regions of the canal segments were more critical than others in maintaining attenuation. The relationship between comfort and canal segment length was not straightforward.

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1. Introduction

In extremely noisy work environments, hearing protection that provides high levels of attenuation is necessary. Critical factors that contribute to high attenuation in earplugs include an airtight seal in the ear canal and a deep insertion (in the case of premolded or formable earplugs) or long canal segment (in the case of custom-molded earplugs). An airtight seal is important because an acoustic leak, or air pathway between the earplug and ear-canal wall, is the most efficient way for sound to bypass an earplug and reach the cochlea (Macrae, 1990). Pirzanski et al. (2000) found that loosely-fitting custom earmolds provided less attenuation than snugly-fitting earmolds, presumably due to acoustic leaks.

Insertion depth or canal segment length is also important for achieving high attenuation (e.g., Du et al., 2008). Norris et al. (2011) created a set of earmolds for an anatomically correct ear canal in a head simulator. The earmolds varied only in the length of the canal segment. Norris et al. found that attenuation increased with canal segment length at a rate of approximately 1.5 dB/mm up to a length of 15 mm. Lengthening the canal segment by an additional 2.9 mm did not increase attenuation.

The phenomenon of greater attenuation with a longer canal segment is related to the anatomy of the ear canal. The human ear canal has two bends along its length, the first one just medial to the aperture of the ear canal, and the second one medial to the first. The lateral portion of the ear canal is cartilaginous, while the medial portion is osseous. The cartilage-bone junction (CBJ) is located in the vicinity of the second bend. The ear canal often narrows between the first and second bends (Alvord and Farmer, 1997; Nielsen and Darkner, 2011). This narrowing can facilitate an airtight seal if the earplug extends deeply enough. In related work, Macrae (1990) showed that hearing-aid earmolds with longer canal segments were more likely to maintain an
airtight seal than were earmolds with shorter canal segments. Furthermore, bone-
conducted sound can cause the ear-canal walls to vibrate. These vibrations are trans-
mitted to the cochlea via the normal air-conduction route. An earplug with a long
canal segment could provide greater attenuation than an earplug with a shorter canal
segment by reducing canal-wall vibration.

Although custom earplugs with long canal segments may be desirable in very
noisy environments, a canal segment that is too long can render an earplug unwear-
able. Specifically, canal segments that reach or go beyond the CBJ can cause discom-
fort or even pain because the osseous portion of the ear canal is very sensitive
(Pirzanski, 1997).

Attaining maximum attenuation while maintaining wearability, then, is chal-
ling but important in high-noise environments. In this pilot study, we investigated
the effect on attenuation of varying the canal segment length of custom-molded ear-
plugs fitted to four adult human subjects. We used a within-subjects design, in which
each subject’s earplug was modified over multiple visits to the laboratory, to eliminate
variables related to earplug manufacture or ear-canal configuration. In this way, we
were able to document not only that longer canal segments provide greater attenua-
tion—which was already known—but the form of the function relating attenuation to
canal segment length for each individual. Anecdotal reports of comfort were obtained
as well.

2. Methods
2.1 Participants
Two men and two women participated in the study (mean age = 24.8 yr; SD = 0.5).
Each participant had normal hearing, no air-bone gaps, clear and unremarkable ear
canals, and no evidence of outer- or middle-ear pathology. The ear with better air- and
bone-conduction thresholds was the test ear (left ear for subjects 1, 3, and 4; right ear
for subject 2). All procedures were approved by the University of Connecticut IRB
and conducted in compliance with all federal regulations governing the protection of
human subjects.

2.2 Custom earplugs
The second author (S.C.) had recently completed a Standardized Ear Impression
Technique course offered by Westone Laboratories, Inc. She took binaural closed-jaw
impressions of the participants’ ear canals using vented foam ear dams, a cartridge
impression gun (Westone Laboratories, Inc., S-50), and silicone impression material.
Each impression was examined to be sure that its surface was smooth with no gaps,
the canal portion clearly extended beyond the second bend of the ear canal, the concha
portion was full and well-defined, and anatomical landmarks such as the first and sec-
ond ear-canal bends were clearly visible.

Custom-molded earplugs (CMEPs) were manufactured by Westone Laboratories, Inc. from these impressions. The CMEPs were made of solid silicone
with no vents. As received from the manufacturer, the canal portion of each test-ear
CMEP clearly extended past the second bend and all landmarks were plainly visible.

2.3 Earplug modification
During the course of data collection, the canal segment of each test-ear CMEP was
systematically shortened in 2-mm increments. Prior to data collection, several markings
were drawn freehand on the earplugs to serve as visual references for the subsequent
modifications. Four views of the earplug were employed: the superior horizontal view
(i.e., the view of the CMEP as it would appear in the ear canal looking down from
above), the inferior horizontal view (i.e., the same view of the CMEP, but looking up
from below), the anterior vertical view (i.e., the view of the CMEP as it would appear
in the ear canal looking from front to back), and the posterior vertical view (i.e., the same view of the CMEP, but looking from back to front).

First, the axis, or center, line of the canal segment was drawn on each of the reference views. Each axis line followed the curves of the canal segment. Second, the aperture ring (i.e., the junction of the concha portion and the canal segment) was located by encircling the most lateral part of the canal segment with cotton crochet thread. The aperture ring was drawn on the CMEP and served as the reference point for all canal segment length measurements. As a precaution, the intersection of each axis line with the aperture ring was marked with a pinhole. The pinholes created a consistent reference in the event that any markings wore off. Third, six rings were drawn around the canal segment to mark the lengths to which it was to be shortened. Each ring was drawn so that it intersected the superior horizontal axis at a right angle, and so that the cut plane of the canal segment was orthogonal to the direction of the canal segment at that point. Adjacent rings crossed the superior horizontal axis 2 mm apart.

Canal segment length was measured from the aperture ring to the tip in the superior horizontal view. This was done by placing one end of a length of crochet thread at the aperture ring, following the contours of the axis line to the tip, marking the thread at the tip, and then measuring the thread length. The mean of three measurements was taken in all cases.

The tip of the canal segment of the CMEP was abraded to the appropriate length using a dental drill (Buffalo V35 Handpiece System) with a blue grinding stone suitable for use with silicone material. The tip was then tapered slightly for comfort and ease of insertion. No other part of the CMEP was modified.

2.4 Earplug attenuation measurement

Earplug attenuation was measured for 1/3-octave-band-noise center frequencies of 125, 250, 500, 1000, 2000, 3150, 4000, and 6300 Hz using a real-ear-attenuation-at-threshold (REAT) procedure in the sound field. Stimulus generation and response acquisition were controlled with the Fitcheck2 Insert Hearing Protector Attenuation Measurement System (Michael and Associates, Inc.) connected to a Dell Optiplex 960 desktop computer with a SoundMAX HD Audio sound card. Stimuli were routed to three Electro-Voice SX100+ loudspeakers located in a single-walled, sound-treated booth (IAC model 403). Speaker output levels remained stable across test sessions. The subject controlled the level of the stimulus with a handheld response button. Hearing thresholds were measured with the test ear alternately unoccluded and occluded by the CMEP. The attenuation at a given test frequency was the difference between the occluded and unoccluded thresholds at that frequency. All testing was conducted with the non-test ear occluded by a deeply inserted foam earplug (3M™ E-A-R™ Classic™ PLUS) covered by an earmuff (Peltor Optime 101 H7A).

2.5 Procedures

Following the initial visit to the laboratory at which earmold impressions were taken, each subject made seven visits for data collection (hereafter, visits 1–7). At each visit, the subject completed four REAT tests with the test-ear CMEP.

At visit 1, the subject was tested with the unmodified CMEP. Before each subsequent visit (visits 2–7), the canal portion of the subject’s CMEP was shortened by 2 mm, as described above. In all, seven canal lengths were tested (the original length and six shorter lengths), representing a total shortening of 12 mm. At the end of each visit, subjects were asked whether they found the CMEP comfortable to wear.

3. Results

Figure 1 shows attenuation at each test frequency as a function of CMEP canal segment length for each subject. Within each individual figure, each data point is the
mean of the four attenuation values measured at that visit. Standard deviations about
the means are not shown for clarity; they ranged from 0.5 to 8.5, with 93% of the val-
ues < 5. The dotted line in each figure represents the personal attenuation rating (PAR)
calculated for each length. The PAR is a single-number estimate of the amount of pro-	ection provided by a hearing protector. Details of its calculation can be found in
Michael (1999). The photograph above each set of data points for a given canal length
shows the superior horizontal view of the unmodified earplug, with each canal segment
length labeled with the corresponding laboratory visit number. A “smiley-face” is positioned above the canal
segment length at which the subject first reported that the earplug was comfortable to wear. See text for further
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details.

Table 2 lists approximate “noise reduction ratings” reported by Norris et al.
(2011) for earmolds tested in a head simulator and the personal attenuation ratings of
the CMEPs in the present study, for approximately matching canal segment lengths.
This table is provided for informational purposes only. Although it is tempting to as-
cribe differences in the attenuation values between the studies to the use of a head sim-
ulator versus human subjects, other methodological differences and the small amount
of data make this conclusion premature.
4. Discussion

In this study, we measured the attenuation of CMEPs whose canal portions were systematically shortened in 2-mm increments. For all subjects and frequencies, attenuation tended to decrease as the canal segment was shortened. The effect was greater at mid- to low frequencies (\(<1000\) Hz) than at high frequencies (\(\geq 2000\) Hz), with the exception of 4000 and 6300 Hz for subject 1 (see Table 1). The median decrease was 25 dB at mid- to low frequencies (range: 20–40 dB) and 10 dB at high frequencies (range: 3–27 dB).

The decrease in attenuation was not linear. For three out of four subjects, critical regions of the canal segments were identified whose removal caused attenuation to drop sharply at more than one frequency. This phenomenon is most easily observed in the data for subject 2. Attenuation at 125, 250, 500, and 1000 Hz changed little across visits 3, 4, and 5, and between visits 6 and 7. However, a steep drop in attenuation occurred between visits 5 and 6 at these frequencies. The 2-mm portion of the canal segment that was removed following visit 5 fell between the first and second bends. For subject 1, steep decreases in attenuation tended to occur between visits 4 and 6, depending on frequency. The critical region in this case fell at and slightly beyond the second bend. For subject 3, steep decreases occurred between visits 3 and 4 or 5 and 6, again depending on frequency. These critical regions fell medial to the second bend and just lateral to the second bend, respectively. For subject 4, changes in attenuation appeared to be more consistent, with no readily apparent critical regions. Since the shortest canal length tested for this subject was 6 mm, it is possible that an existing critical region was not identified.

Anecdotally, the two male subjects found their CMEPs to be comfortable at each visit, even when the canal segment extended past the second bend. Neither of the female subjects found their CMEPs comfortable until the portion that lay beyond the second bend was removed. For these two subjects, some attenuation had to be sacrificed in order to make the earplugs wearable without discomfort. Note, however, that the subjects were not given the opportunity to acclimate to their CMEPs by increasing wearing time gradually over several days, as would typically occur in a hearing conservation program (assuming of course that the CMEPs were not so painful as to be

### Table 1. Difference in attenuation (in dB) between the longest and shortest canal segment lengths, for each subject and test frequency.

<table>
<thead>
<tr>
<th>Subject</th>
<th>125 Hz</th>
<th>250 Hz</th>
<th>500 Hz</th>
<th>1000 Hz</th>
<th>2000 Hz</th>
<th>3150 Hz</th>
<th>4000 Hz</th>
<th>6300 Hz</th>
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<td>24</td>
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<td>11</td>
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<td>28</td>
<td>26</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>3</td>
</tr>
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</table>

### Table 2. Comparison of data from Norris et al. (2011) with data collected in the current study. Data reported are “noise reduction ratings” (Norris et al.) and personal attenuation ratings (subjects 1–4), in dB, for several canal segment lengths.

<table>
<thead>
<tr>
<th>Length (mm)</th>
<th>Norris et al. (2011)</th>
<th>Subject 1</th>
<th>Subject 2</th>
<th>Subject 3</th>
<th>Subject 4</th>
</tr>
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<tr>
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<td>~45</td>
<td>36</td>
<td>—</td>
<td>41</td>
<td>43</td>
</tr>
<tr>
<td>14–15</td>
<td>~45</td>
<td>34</td>
<td>41</td>
<td>37</td>
<td>40</td>
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<tr>
<td>9–10</td>
<td>~32</td>
<td>17</td>
<td>36</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>4–5</td>
<td>~28</td>
<td>15</td>
<td>19</td>
<td>19</td>
<td>—</td>
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<tr>
<td>0</td>
<td>~18</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</tr>
</tbody>
</table>
intolerable). Comfort at first fitting may not be indicative of eventual comfort and acceptance of the CMEP.

Several issues should be addressed in future work. First, a larger sample size is necessary to improve generalizability of these results. Second, the degree to which the canal segment fills the ear canal along its entire length (i.e., the snugness of the fit in the ear canal) should ideally be controlled. In a second part of their study, Norris et al. (2011) showed that decreasing the girth of the canal segment proportionally along its entire length dramatically reduced attenuation. In the current study, if the snugness of fit happened to vary along the length of the canal segment, then it could have confounded the effect of length on attenuation. Third, a greater range of canal segment lengths should be tested. Ideally, the canal segment should be shortened to 0 mm, or until some minimum criterion of acceptable attenuation is met. Finally, the dimension of comfort should be investigated more systematically, preferably in an environment more representative of real-world conditions (e.g., allowing a period of acclimation to the CMEPs).

5. Conclusions

The length of the canal segments of the CMEPs tested in this study affected the amount of attenuation provided, with longer canal segments giving greater attenuation. The effect was generally more pronounced at mid- to low frequencies (≤1000 Hz) than at higher frequencies (>2000 Hz). Some regions of the canal segments appeared to be more critical than others in maintaining attenuation. These regions, which varied from individual to individual, included the area between the first and second bends and other regions in the immediate vicinity of the second bend. To ensure maximal attenuation, results suggest that the canal segment of a CMEP should extend beyond the second bend. Some individuals may find that canal segments of this length are uncomfortable at first fitting, as did two out of the four subjects in this study. A period of acclimation is recommended so as not to sacrifice attenuation by modifying the CMEP unnecessarily.

Acknowledgment

This study was funded by the Office of Naval Research.

References and links

1In 16 out of 32 cases, the difference shown in Table 1 was not the largest for that subject and frequency, either because the attenuation measured at the longest canal length was not the greatest, or the attenuation measured at the shortest canal length was not the least, or both. Replacing those numbers in Table 1 with the maximum differences did not change the overall pattern of the results.


