The Importance of Auricular Prostheses for Speech Recognition

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Objectives: To examine the effects of an auricular prosthesis on sound levels at the entrance of the ear canal by measuring the auricular prosthesis transfer function (APTF) and to determine the effect of the prosthesis on speech recognition in noisy hearing conditions.

Methods: Eight prostheses were used to measure the APTF. A microphone at the entrance of the ear canal measured sound pressure levels with the prosthesis present or absent while the head was rotated 360° at 30° increments. The Hearing in Noise Test was modified by the APTF to simulate the absence of an auricular prosthesis. Speech recognition was measured by testing 11 subjects with the unmodified Hearing in Noise Test and the modified Hearing in Noise Test.

Results: The APTF changed with the head’s position relative to the speaker. The mean (SD) maximal gain provided by an auricular prosthesis was 8.1 (2.7) dB at 4.6 (1.0) kHz and 9.7 (1.7) dB at 11.5 (0.9) kHz at 0° rotation. During speech testing, the auricular prosthesis improved the mean (SD) signal to noise ratio by 1.7 (1.7) dB at 0° (P<.001), 0.9 (2.2) dB at 90° (P=.04), and 0.5 (2.3) dB at 180° (P=.52).

Conclusions: The acoustic gain provided by an auricular prosthesis increases speech recognition in noisy environments. Auricular prostheses not only restore aesthetics but also improve hearing.

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Auricular prostheses restore the appearance of patients with large auricular defects caused by cancer, surgery, or trauma. Although the aesthetic benefit is widely accepted, it remains unknown whether an auricular prosthesis benefits hearing. Restoration of normal hearing is important for a subset of auricular prosthesis wearers who have normal outer and middle ear anatomy and normal cochlear function. Examples include patients who undergo auricular resection for treatment of cutaneous malignant neoplasms and patients who incur auricular avulsion after a traumatic accident. Their external auditory canal is usually intact, and the remainder of their auditory system should function normally. In these patients, the physician must strive not only to correct the aesthetic defect caused by the missing pinna but also to correct the hearing loss caused by its absence.

Although (to our knowledge) no authors directly report the number of patients with an auricular prosthesis who have an otherwise functional auditory system, the number may be estimated from studies of the population using prostheses. In a study of children with severe auricular defects who underwent reconstruction with a prosthesis, most patients have an auricular defect from a congenital malformation known as “microtia.” These patients usually have concomitant external auditory canal atresia, and an auricular prosthesis cannot benefit their hearing because of the absence of an external auditory canal. However, a significant number of patients with auricular prostheses have acquired auricular defects. Westin et al in a long-term study of auricular prostheses users of all ages reported that 30% sustained their defect from tumor resection, 8% from trauma, and 3% from burns. Findings from studies focusing on pediatric auricular prostheses users indicate that 4% to 27% sustained their defect from trauma, 1% to 9% from burns, and 1% from tumor resection. Patients with acquired defects likely have a normal external auditory canal and middle ear and a functional cochlea. For these pa-
patients, an auricular prosthesis not only is essential to their appearance but also may affect hearing. Patients with acquired defects may have a hearing loss from their absent auricle, but the remainder of the auditory system is preserved and functional. Although the total number of patients involved is small, the improvement of their conductive hearing loss may be significant.

To our knowledge, only 1 study in the literature has studied the audiometric effects of auricular prostheses. Reisberg and Lipner described 4 patients with severe auricular defects but intact ear canals who chose reconstruction with an auricular prosthesis. Each patient underwent pure-tone audiometric evaluation with and without the prosthesis, as well as objective measurement of sound from a microphone in the external auditory canal with the auricular prosthesis present and absent. The sound levels at the eardrum with the prosthesis present and absent at 0°, 45°, 90°, and 180° using 8 frequencies (range, 0.25-6 kHz) showed that the prosthesis provided an acoustic gain, especially at high frequencies. However, the results varied drastically among patients. These variations may have resulted from different prosthesis shapes or from differences in the head, neck, or external auditory canal shape among patients. Measuring the acoustic gain of auricular prostheses in a model system avoids these variations in the head, neck, and external auditory canal shape. Recognizing these advantages, the present study measured the acoustic gain of auricular prostheses in a model system. Furthermore, the model system eliminated the need for each patient to sit completely still for several hours during the detailed collection of data, sparing the patient from a lengthy testing session.

In addition to quiet hearing conditions, it would be important to extend the study by Reisberg and Lipner to examine the contribution of auricular prostheses to hearing in noisy conditions. Noisy hearing environments challenge the listener and often prevent communication. To function in this difficult hearing condition, more acoustic information is necessary to comprehend speech. Ample experiments have shown that the presence of masking noise or interfering speech decreases speech recognition drastically with increasing noise level.

Experiments among individuals with normal hearing have shown that the pattern of peaks and valleys in the acoustic frequency spectrum (spectral cues), interaural time differences, and interaural level differences enhance speech perception. However, if the amount of acoustic information to the listener is kept constant, speech recognition should decrease in noisy environments.

The specific aims of this study were to determine whether the lack of an auricular prosthesis reduced the amount of information to a listener, resulting in decreased speech recognition in noisy listening environments, and to investigate whether the presence of an auricular prosthesis restored the hearing loss. The study consisted of the following 2 parts: (1) The auricular prosthesis transfer function (APTF) of an auricular prosthesis was characterized using a model system. (2) The APTF was then used to modify the Hearing in Noise Test (HINT) to model a missing auricular prosthesis to a test subject with normal hearing. In this step, the contribution of the prosthesis to speech recognition was quantified.

### APTF Analysis

**Auricular Prostheses and Casts**

Eight different silicone rubber auricular prostheses and the corresponding dental stone casts of the auricular defect of patients with complete absence of the pinna were duplicated using a bank of stored casts and molds (Figure 1). To duplicate each auricular prosthesis, silicone rubber (Platinum Silicone Elastomer; Factor II, Inc, Lakeside, Arizona) was poured into an existing mold and was allowed to harden. To create the duplicate cast, boxing wax (Patterson Dental Company, St Paul, Minnesota) was applied to the periphery of the cast. Silicone rubber (3110 RTV Silicone Rubber Encapsulant, RTV Diluent, and #4 Catalyst; Dow Corning, Midland, Michigan) was then poured on top of the cast to create a reverse copy, or impression, of the cast. Pouring dental stone (Cocetyl Type III Dental Stone; GC America Inc, Alsip, Illinois) onto this reverse silicone copy created the exact stone duplicate of the original cast. Each duplicate cast with the corresponding prosthesis was termed a specimen. Details of each specimen are given in Table 1. Each silicone auricular prosthesis was then attached to the corresponding plaster cast with cyanoacrylate glue (Loctite 404; Loctite North America, Rock Hill, Connecticut) in the location where the prosthesis keys into the cast's contour. If silicone covered the external auditory meatus, an approximate 7-mm hole was cut out of the prosthesis. Next, a 7-mm hole was drilled into the site of the external auditory meatus in each of the plaster casts (Figure 1).

**Insetting Specimens Into Model Heads**

A life-sized plastic foam (Styrofoam) head was obtained, and an approximate 12-mm hole was drilled through the width of the entire head at the location of the external auditory meatus. Each specimen was mounted flush into the model head using stainless fixture setting compound (William H. Harvey Co, Omaha, Nebraska) to drive a dual audio speaker (Dual L201, Gebrüder Steidinger, St Georgen, Germany). The signal was impedance matched by an audio amplifier (Transnova P1500, set at 0 dB; Hafler, Tempe, Arizona) to drive a dual audio speaker (Dual L201, Gebrüder Steidinger, St Georgen, Germany).

**Sound Source**

A white noise electrical voltage command was generated by an arbitrary waveform generator (HP 33120A; Hewlett-Packard Company, Palo Alto, California). The signal was impedance matched by an audio amplifier to drive a dual audio speaker.

**Sound Level Measurements**

Measurements were made in an anechoic chamber with the sound source 2 m from the model head at the same vertical height as the external auditory meatus. Each specimen was mounted in a...
model head and was rotated in the axial plane. The 0° position was defined as the direction of view with the head directly facing the speaker, the 90° position was defined as the specimen facing the speaker, and the 180° position was defined as the head facing directly away from the speaker. The model head was rotated at 30° increments, and measurements were taken at each position. Once measurements were made from a full rotation, the silicone prosthesis was removed, and the measurements were repeated at each rotation position with the prosthesis absent.

For the measurements, a ¼-in (3.18-mm) microphone (Brüel & Kjær, Norcross, Georgia) was inserted from the opposite side through the plastic foam head into the external auditory meatus hole so that the tip of the microphone was flush to the surface of the cast (Figure 2). A 2-mm-long segment of plastic tubing (1.59-mm thick and 3.18-mm inner diameter) surrounded the tip of the microphone and occluded the hole at the external auditory meatus (Figure 1). Voltages produced by the microphone were amplified by a microphone amplifier (NEXUS; Brüel & Kjær), were filtered with an antialiasing filter (corner frequency of 20 kHz), and were sampled at a rate of 100 kHz using a computer input/output (I/O) board (DAS1600; Keithley Instruments, Inc, Cleveland, Ohio).

While the noise was played continuously from the speakers, 40-millisecond time segments were recorded, and a fast Fourier transform (FFT) using 8192 data points was calculated from the segment. The FFTs from 100 segments were used to calculate the mean sound level at the microphone for any given experimental condition (prosthesis or no prosthesis) and for the different orientations of the head toward the sound source.

DATA ANALYSIS

Following the measurements, the averaged FFTs were plotted for each specimen using commercially available software (IGOR; WaveMetrics, Lake Oswego, Oregon). The gain of the auricu-
lar prosthesis was determined for each angular head position by calculating the ratio between the sound levels with the prosthesis present and absent (Gain = 20 \times \log\left(\frac{\text{sound level}_{\text{prosthesis present}}}{\text{sound level}_{\text{prosthesis absent}}}\right)\). Original data were smoothed using spline functions^{16} and are shown in the figures by a black solid line as the smoothed data. This procedure minimizes

\[ \int_{x_0}^{x_\infty} g'(x)^2 \, dx \]

among all functions \( g(x) \) such that

\[ \sum \left( \frac{g_i(x) - y_i}{\sigma_i} \right)^2 \leq S, \]

where \( g_i(x) \) indicates the value of the smooth spline at a given point; \( y_i \), the \( y \) data at a given point; \( \sigma_i \), the standard deviation of this point; and \( S \), the smoothing factor (for these data, \( S = 2 \)). Furthermore, data from all 8 specimens were averaged. The standard error was calculated.

**TRAGUS EXPERIMENT**

The casts of specimens A through C were duplicated and were labeled as being without tragus (w/oT) (casts A-C\textsuperscript{w/oT}). The tragus on casts A-C\textsuperscript{w/oT} were hurried down until flush with the surrounding contour. These casts were inset into the model head, the corresponding prostheses were affixed, and the acoustic measurements and data analysis were performed as already described. The APTF for specimens A through C with tragus was compared with the APTF for specimens A through C without tragus.

**SPEECH TESTING**

**Modification of the HINT**

Modifications of the HINT were made to mimic the absence of the pinna for an individual with normal hearing. In other words, instead of removing the pinna, which is impossible in an individual with normal hearing, the acoustic effects caused by the absence of a pinna were simulated. In detail, the sentences and the noise of the standardized HINT were obtained on a CD. The test sentences were saved as individual files in “.AVI” format and were then converted into “.WAV” format. Commercially available software (MatLab, MathWorks; MathWorks Inc, Natick, Massachusetts) was used to divide each waveform into subarrays of 8192 data points. Next, the FFT was calculated for each of the subarrays and was divided by the APTF determined in the first part of this study. In other words, at the frequency points for which the APTF was 1, the FFT magnitude obtained from the sound track remained unchanged, while the magnitude of the sound track was reduced for frequency points at which the transfer function was greater than 1 or was increased for frequency points at which the transfer function was less than 1. The changed FFT of each subarray was then transferred into a novel waveform file using the inverse FFT. All corresponding file segments were concatenated to an altered sound track. In other words, each sound track of the HINT test was adapted to the APTF. Because the APTF changed for different angles around the head, changes were made for all given locations of the speaker.

**Selection of Test Subjects**

Before physical examination and administration of the speech test, all procedures were explained to the subjects, and a consent form was signed. Otoscopic examination was performed to rule out anatomic abnormalities. Hearing was tested in an anechoic chamber before speech testing to ensure normal hearing. The speech test was then given to 11 young English-speaking adults with normal hearing.

**Speech Test**

The speech test was administered in an anechoic chamber. Before applying the speech test, the setup was calibrated. A 1/8-in (3.18-mm) microphone (Brüel and Kjær) was placed at the position of the head of the volunteer. The sound levels from the 2 speakers were calibrated to 65 dB sound pressure level using a 1-kHz test tone. The test subject occluded the left ear with a standard earplug (E-A-R Classic; E-A-R, Indianapolis, Indiana). During the speech test, the speech signal always played from the speaker in the 0° position, which was in front of the test subject. The noise signal played from a second speaker that rotated among the following 3 positions: 0° (subject facing the noise source), 90° (noise source lateral to the test ear), and 180° (subject facing away from the noise source). The sound level of the speech signal was increased and decreased in steps of 1 dB until 100% of the sentences were understood. The resulting sound levels for 100% correct were averaged for sentences 6 through 10 in each track. To compensate for learning, we played a different track for each trial and repeated the 0° trial with the prosthesis present at the end of each subject’s test. The unmodified HINT and the modified HINT were administered with the noise source at each position. The results from the prosthesis present unmodified HINT...
The mean maximal gain for all specimens at each head position was determined using Tukey test with a 1% significance criterion. Significant changes were detected by performing 1-way analysis of variance with a 1% criterion for significance. If a significant overall change was found for sound level at the entrance of the external auditory canal, corresponding to a negative gain (Figure 4). For 11.5 kHz, positive gains were observed when the head rotation was between −30° (equivalent to 330°) and 90° (Figure 4). For the remaining head rotations, a negative gain was seen.

To determine the effect of the tragus, some of the casts were modified by removing the tragus. The differences between the APTF for specimens A through C with tragi and the APTF for specimens A through C without tragi were graphed (data not shown). Little difference was observed with the tragus absent.

SPEECH TESTING

The 11 test subjects had normal results on otoscopic examinations and normal hearing thresholds (data not shown). Of 11 test subjects who underwent speech testing, 1 (subject K in Table 2) was excluded from the data analysis because the results were greater than 4 SDs beyond the mean compared with the rest of the subjects. These anomalous data were likely due to a recording error.
ror in which the CD from the modified speech test was mistakenly recorded as the unmodified speech test. The mean (SD) thresholds for the unmodified HINT (prosthesis present) were 54.9 (2.1) dB in 60-dB noise at 0° (which corresponds to a -5.1-dB signal to noise ratio), 54.7 (3.0) dB in 60-dB noise at 90° (which corresponds to a -5.3-dB signal to noise ratio), and 55.6 (5.6) dB in 60-dB noise at 180° (which corresponds to a -4.4-dB signal to noise ratio). The signal to noise ratio for the unmodified speech test (prosthesis present) was significantly better than that for the modified speech test (prosthesis absent). The mean (SD) differences were -1.7 (1.7) dB at 0° (P < .001), -0.9 (2.2) dB at 90° (P = .04), and -0.5 (2.3) dB at 180° (P = .52). Speech testing data are given in Table 2.

There were 2 major findings in this study. (1) Auricular prostheses provide an acoustic gain at certain head positions and frequencies. (2) This acoustic gain is clinically significant because it benefits speech recognition in noise.

The acoustic gain provided by an auricular prosthesis was determined by calculating the APTF. Although the normal human pinna transfer function has been determined,17-21 the results from this experiment represent new data. To our knowledge, no studies have reported the gain or transfer function for auricular prostheses.

Although the present study is the first to report the APTF, multiple groups have obtained results similar to ours for the normal human pinna. Following calculations by von Békésy22 of the sound level at the tympanic membrane for a given free-field sound pressure, Wiener and Ross23 were the first to measure the pressure distribution along the auditory canal for a given sound field. They measured sound levels between 0.2 kHz and 8 kHz in healthy human subjects at different locations along the ear canal. Similar to our results, they observed a 10-dB to 12-dB acoustic gain at 4 kHz between 0° and 90°. Shaw20 reviewed data pertinent to the transformation of sound pressure level from the free field to the eardrum. The review by Shaw also contained data from measurements for frequencies above 8 kHz. Similar to the results from the present study, a maximum sound pressure gain of 10 dB was observed at 4 kHz and at 12 kHz. Middlebrooks et al24 and Mehrgardt and Mellert25 provided further measurements of the pinna transfer function in humans; they found transfer function maxima at 3 kHz and at 9 kHz. While these earlier studies evaluated the transfer function of the external ear, including the pinna and the external ear canal, our study focuses on the acoustic effect of an auricular prosthesis alone. The results show that auricular prostheses are more than aesthetic devices; they provide a substantial sound level increase at certain head positions.

At this point, we have not determined which part or parts of an auricular prosthesis most increase the acoustic gain. In other words, we do not know whether the size of the prosthesis, the shape of the concha, or any other part of an auricular prosthesis most contributes to acoustic gain. As part of the acoustic experiments, we looked at the effect of the tragus to see if the presence of the tragus on the prosthesis or cast changed the acoustics. Little difference was measured between specimens with and without a tragus. Teranishi and Shaw19 and Shaw20 demonstrated in 2 articles that the shape of the pinna and concha is crucial for the frequency response properties of the external ear. Knowing that the tragus had little effect on the APTF, we assume that differences in the APTF between specimens must stem from another auricular structure.
While the first series of experiments in this study showed that an auricular prosthesis provides an acoustic gain at certain head positions and frequencies, the second part of the study determined whether this acoustic gain is clinically relevant. In other words, the second part of the study answers the question whether the gain measured in a model system actually improves a patient’s hearing. The results from the unmodified HINT that was used in the present study are in agreement with reports in the literature. For example, Nilsson et al measured with the HINT a mean threshold of 69 dB (A) in 60-dB noise. In a similar setting, our measurements revealed at 0° azimuth a mean threshold of 55 dB in 60-dB noise. The mean thresholds for the modified HINT (prosthesis absent) were elevated by 1.2 dB. The results of this study support the view that the gain provided by an auricular prosthesis benefits hearing by improving speech understanding in noisy environments. Although the differences are not large in terms of decibels, it has been shown that a 1-dB improvement of the signal to noise ratio improves speech intelligibility by 11% to 19%.

### CONCLUSIONS

Auricular prostheses provide an acoustic gain at certain head positions and frequencies, and this acoustic gain is clinically relevant because it benefits speech recognition in noise. In some individuals, auricular prostheses not only effectively restore aesthetics but also may improve hearing. To verify the results of the present experiments, the main outcome measures described in this study will be used to obtain future measurements from individuals who wear auricular prostheses.
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