Comparison of Real-world Bandwidth in Hearing Aids vs Earlens Light-driven Hearing Aid System

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This study compares the effective bandwidth and maximum gain before feedback of the Earlens device—a light-driven (as opposed to acoustically driven) hearing aid system—to six receiver-in-the-canal (RIC) hearing aids in similar conditions. Mean bandwidth for the six RICs was 890-4,400 Hz, with maximum gain before feedback of 22-39 dB. The Earlens bandwidth was 125-10,000 kHz, with a maximum gain before feedback of 55 dB.

The primary goal of a hearing instrument is to increase audibility for the impaired listener. However, basic physics limits the performance of air conduction hearing aids in three important ways:

- **High frequency audibility.** In the hearing aid receiver, the moving mass and inductive reactance of the coil in a small balanced armature limits its output at high frequencies. Increased output sensitivity requires a larger receiver with a larger moving mass, resulting in a corresponding decrease in upper cut-off frequency. The increase in electrical impedance at high frequencies also limits the maximum output.[1]

- **Low frequency audibility.** Hearing aid receivers are high acoustic impedance devices designed to be efficient at producing sound in a small, sealed cavity.[2] Open canal or widely vented fittings increase the volume of the receiver, dramatically reducing low frequency efficiency.

- **Gain before feedback.** Even with the most advanced feedback cancellation algorithm, mechanical coupling and acoustical proximity impose a fundamental limitation to how much gain a conventional hearing aid can deliver before the device begins to feedback.[1]

Background

The majority of research in human speech and voice communication, particularly regarding hearing-impaired listeners, has historically been limited to frequencies below 5 kHz because that was the bandwidth of hearing aids and analog telephone systems. The increase in bandwidth in the telecom world has led to wide-band solutions for speech communication and streaming media. Likewise, in hearing science, research is now evaluating the benefits of higher frequencies.

The extension of high frequency response affects intelligibility even in noisy or complex listening situations.[3-8] Levy et al[8] examined the effects of high frequency cut-off on speech understanding in complex listening environments. Bandwidths up to 10 kHz were tested in normal-hearing and hearing-impaired listeners using the Hearing In Speech Test (HIST), similar to the HINT test,[10] except the masking signals are other talkers, and stimuli contain frequencies up to 20 kHz.[8] In the 2-talker masker condition, extending the high-frequency cut-off from 4 kHz to 10 kHz significantly improved speech intelligibility. These results illustrate that extending the upper bandwidth limit to 10 kHz may improve speech understanding in certain difficult listening situations.

Other studies suggest that a wide bandwidth may deliver more natural sound. Moore and Tan[10] evaluated the perceived naturalness of music and speech as a function of bandwidth in normal-hearing listeners. Perceived naturalness improved with decreasing lower cutoff frequency or increasing upper cutoff frequency. Wider bandwidths increased perceived naturalness of speech, with the largest improvement for a bandwidth of 123 Hz to 10.9 kHz.

In addition to the provision of extended high frequency amplification to accomplish this wide bandwidth, low frequency information improves the naturalness of amplified sound.[10] Low frequency gain is needed to fit reverse slope losses, or any notable low frequency hearing impairment. With current air conduction hearing aids, an occluded dome or custom occluded earmold is required to provide sufficient low frequency output for streaming media with a bandwidth extending to the low frequencies, even for those with normal hearing in the lower frequencies for whom the perceptual trade-off of occlusion may be objectionable.

Some contemporary hearing instruments claim the advantage of bandwidth up to 10 kHz. In order to effectively deliver this broad-spectrum amplification for a typical hearing loss profile, the gain margin before feedback must

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1. The Photon Processor™ collects and applies advanced digital signal processing to sound. The sound information is then transmitted to the Light Tip.

2. The Light Tip encodes the processed sound signal into non-visible light pulses that are projected at the Lens.

3. The light is captured by the Lens which, creates a small electrical current that translates the light pulses into mechanical vibrations that directly vibrate the tympanic membrane.
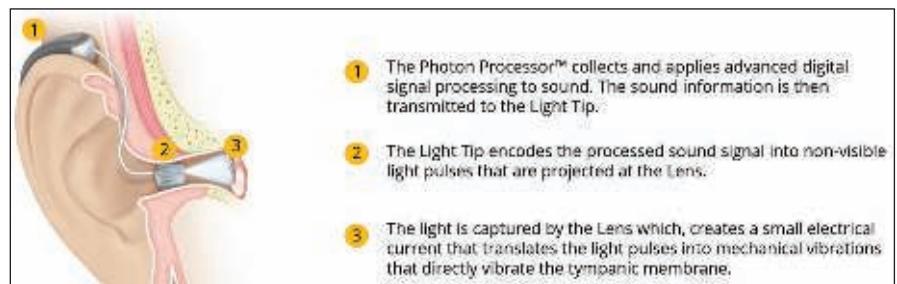
Figure 1. Schematic of the Earlens Light-Driven Hearing Aid.

be sufficient to provide audible output across the spectrum for common sounds, such as speech, where the energy in the high frequencies decreases as the hearing loss typically increases.

The actual real-world bandwidth for current acoustic hearing aids is the subject of this paper and is compared to that of a novel hearing instrument which delivers amplification non-acoustically, the Earlens. The effective bandwidth of the Earlens device overcomes the acoustic limitations described above without occluding the ear, delivering audible gain from 125 Hz to 10 kHz with a high margin of stable gain.[11]

A Light-Driven Hearing Aid System

As shown in Figure 1, the Earlens Light-Driven Hearing Aid overcomes the acoustic limitations of conventional hearing aids by using light to transmit sound information to a transducer that directly drives the tympanic membrane. It consists of three main components: 1) the Tympanic Lens (Lens); 2) a non-occluding custom Light Tip, and 3) the Photon Processor (Figure 2). The custom lens is placed on the tympanic membrane by a trained ENT physician. The custom shape of the Lens and the application of mineral oil on a weekly basis ensure that the device stays in place. A video of the Earlens Hearing Aid is available at: http://earlens.com/professional/the-earlens-device

Study Purpose

To compare the effective bandwidth of the Earlens technology with the latest technology in air-conduction hearing instruments, six competitive open-fit receiver-in-the-canal (RIC) devices were examined. RIC devices were chosen for several reasons: Similar to the Earlens device, RIC devices commonly employ a non-occluded fitting; receivers in RIC devices typically have an extended high frequency response, and the mechanical separation between the microphone(s) and receiver in a RIC device affords the maximum air-conduction gain before feedback. Also, RIC instruments are the most common type of hearing device currently fitted and would be considered appropriate for the target audiometric hearing profile.

Each RIC model was tested as a "system": the device along with its accompanying fitting software. All units were tested in a simulated real-use condition, fit on the ear of a standard test manikin, and with a typical audiogram as the input to the fitting software.

Test Procedure

The following mini BTE RIC hearing devices were tested:

- Oticon Alta2 PRO
- Phonak Audéo V90
- Resound Linx[2] 9
- Siemens Carat 7bx
- Starkey Halo i110
- Widex Unique 440

The basic performance of each device was verified by measuring Full-On Gain, Reference Test Gain, and OSPL90 in the ear simulator and comparing to published data sheets. All devices were within measurement tolerances of the manufacturer's specifications. Devices were programmed to the respective manufacturer's proprietary fitting targets with all non-linear and time-varying signal processing algorithms (noise management features, etc) disabled except for gain and compression. The audiogram shown in Figure 3 was used as input to each fitting algorithm, which is a "typical" hearing profile appropriate for treatment with open-fit RIC devices, and is the mean audiogram from a previous Earlens study

Figure 2. Earlens Hearing Aid Photon™ Processor and Light Tip (top) and Tympanic Lens (bottom).

(submitted paper: Gantz, BJ, Perkins R, Murray MT, et al, "Light-Driven Contact Hearing Aid for Broad Spectrum Amplification: Safety and Effectiveness Pivotal Study," 2016).

A small sound source was positioned 70 cm from the test point in the center of the room and equalized for a flat acoustic response. The center of the manikin head was then placed at the test point for subsequent measurements. The stimulus level at the test point was 65 dB for all tests. Both pink noise and speech spectrum noise (ICRA, Track 2)[12] were used as stimulus signals. The spectra for each were recorded at the test point, both with and without the manikin present (Figure 4).

Devices were tested with an open fitting on an ANSI S3.36 standard[13] manikin equipped with an IEC 60318-4[14] standard ear simulator, yielding equivalent sound pressure levels at the eardrum. The receiver was placed
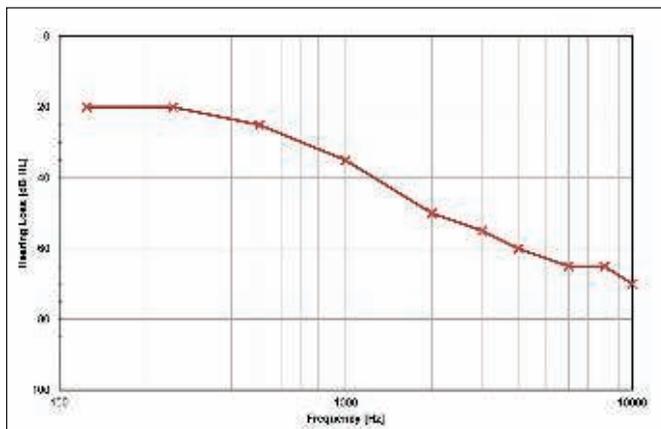

Figure 3. Audiogram used as input for each hearing device and fitting software under test.
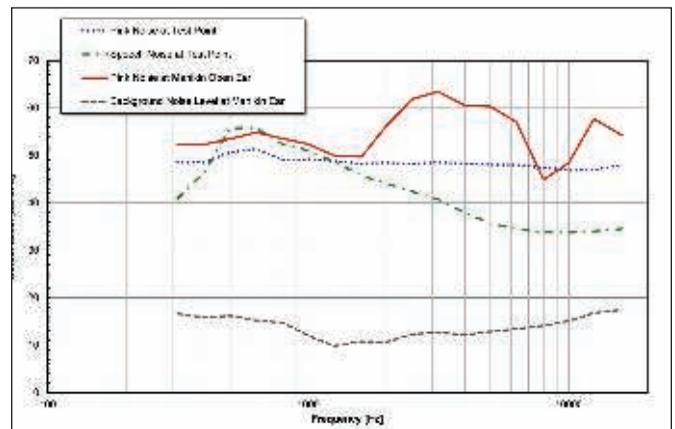

Figure 4. Stimulus and background noise spectra, 1/3 octaves.

into a vented (open) earmold adaptor (GRAS RA 0305) positioned in the canal extension.[15] This ensured a consistent and representative acoustic leakage for all tests in this condition (Figure 5). Measurements were performed on-axis (0° azimuth, 0° elevation), in 1/12 octave bands, yielding simulated in-situ output sound pressure level (OSPL).

The maximum equivalent pressure output (EPO) at the tympanic membrane for the Earlens in Figure 6 was measured on human cadaveric temporal bones using a laser Doppler vibrometer to record the stapes velocity directly in response to the Lens and equating it to stapes velocity and probe microphone measurements at the tympanic membrane location in response to an equivalent acoustic stimulus without the Lens on the ear (same methods as Puria et al[16]). The equivalent EPO for the Earlens device for the same conditions as the RIC devices (65 dB pink noise stimulus, open fit, for the same input audiogram) was computed based on the known response of the system, and is shown in Figure 7.

For each device evaluated, the simulated in-situ gain was calculated as the difference (in dB) between the OSPL measured on the manikin at the (ear) Drum Reference Point (DRP) and the stimulus SPL at the test point, in 1/12 octave bands. Simulated insertion gain was then calculated as the difference (in dB) between the simulated in-situ gain and the open ear manikin response, in 1/12 octave bands. These responses are referred to as "simulated" in standard terminology as they derive from manikin measurements, as opposed to probe microphone measurements on human subjects.[17] The manikin presents realistic but stable and repeatable acoustic conditions.

For comparison, all data were converted to standard 1/3 octaves. The OSPL was converted as the power sum of the 1/12 octave band values comprising each 1/3 octave, while the in-situ gain and insertion gain were converted as the power average of the 1/12 octave band values comprising each 1/3 octave.

Results

Figure 7 shows the OSPL for the open canal fitting of the RIC devices and the widely vented Earlens device, using the typical audiogram as input to the fitting software and pink noise as the stimulus.

Figure 8 shows the OSPL for the RIC devices and the Earlens device using the typical audiogram as input to the fitting software and speech-shaped noise as the stimulus. In addition, the computed audibility threshold is plotted. Audiogram thresholds were converted from dB HL to dB SPL using the Minimum Audible Pressure (MAP) data in Killion.[18] Then 15 dB was subtracted from dB SPL to account for the crest factor of speech[19] and plotted as an indicator of the audibility threshold for speech. The effective bandwidth for the devices are derived from these values.

Effective bandwidth. The real-world bandwidth (Table 1) was calculated using the OSPL data for a speech noise input in 1/12 octave bands and the converted audiogram data plus 15 dB, log frequency interpolated to 1/12 octaves.

The upper limiting frequency (f2) was found as the highest intersection of the OSPL curve for 65 dB speech noise input and the calculated audibility threshold (converted audiogram plus 15 dB to represent the upper frequency limit of speech audibility).[20] The lower limiting frequency (f1) was found as the frequency at which insertion gain for the open-fit condition was less than 8 dB (average of 1/2- and 1/3-gain rules), the minimum gain required to fit the input audiogram at the lowest frequencies. The resulting effective band-

widths for each device are shown in Table 1.

Maximum gain before feedback. Maximum gain before feedback was found for each RIC device in the open-fit condition by increasing the gain in each programming band until feedback occurred, and then reducing the gain to just below this level, using the fitting software. The manikin OSPL was then measured and the simulated in-situ and simulated insertion gain were determined as above. The stimulus for this measurement was speech shaped noise (ICRA Track 2).[12]

The resulting maximum simulated insertion gain before feedback for each RIC device appears in Figure 10, and are plotted along with acoustic measures of the Earlens maximum gain before feedback derived from direct acoustic measures on human subjects[11] with the microphone located in the processor. To determine the gain margin in the lower frequencies, temporal bone estimates were used.[16]

Discussion

This study was intended to evaluate the effective bandwidth of RIC devices and Earlens

Figure 5. Cut-away view of vented ear mold insert, ear canal extension, and ear simulator used for open-fitting condition.
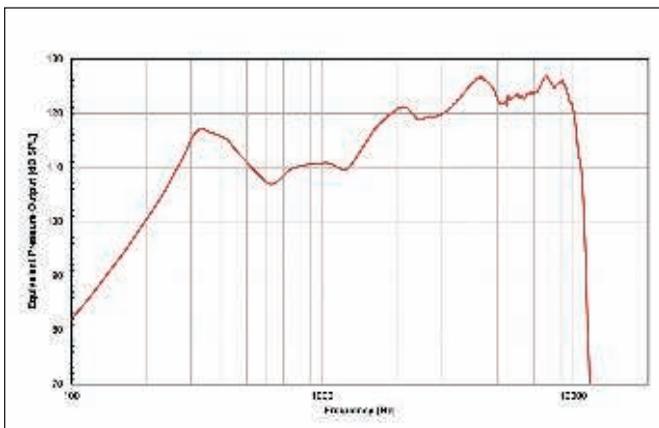
Figure 6. Equivalent sound pressure output for the Earlens for maximum velocity measured at the stapes, average of four measurements.
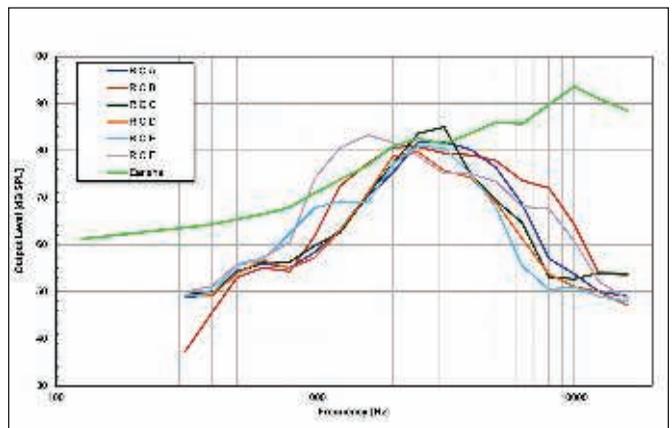
Figure 7. Simulated in-situ OSPL for open canal, 65 dB pink noise stimulus, 1/3 octaves.
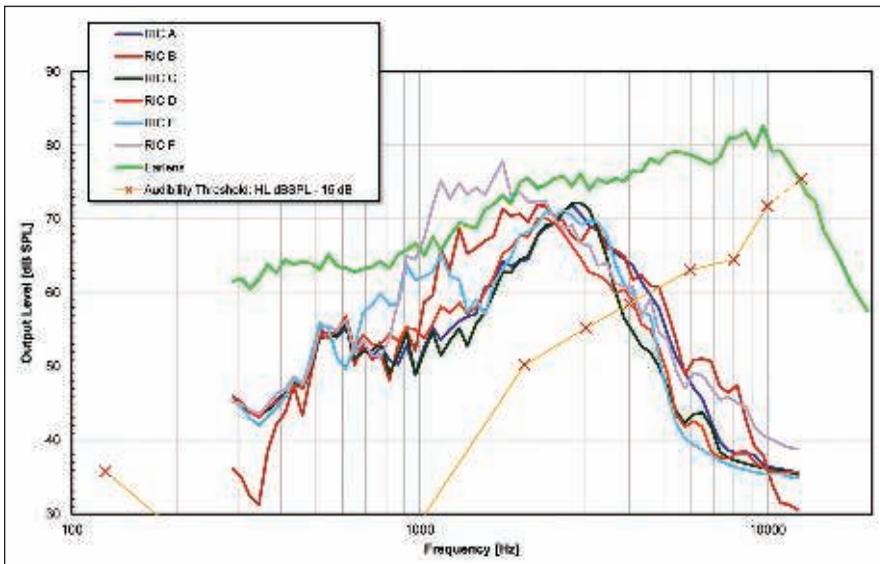
Figure 8. Earlens vs. RIC in-situ OSPL, with calculated audibility threshold for open canal, 65 dB speech noise stimulus, 1/12 octaves (see text).
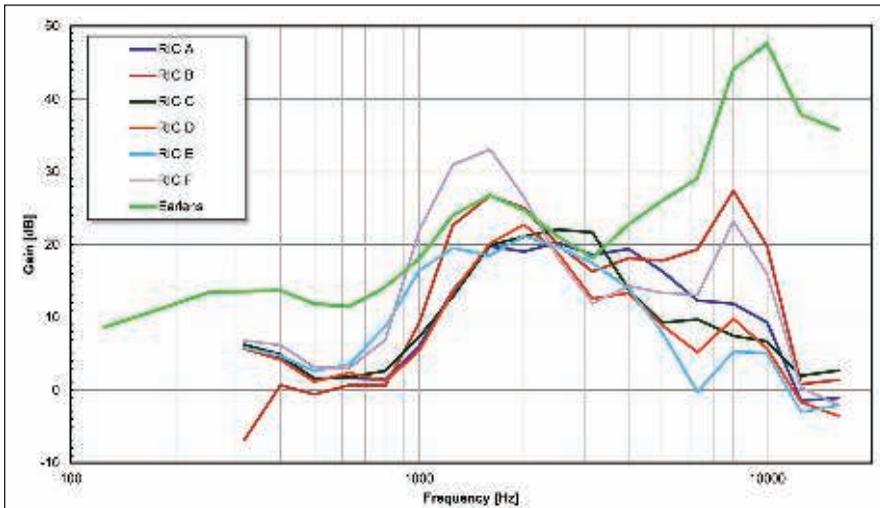

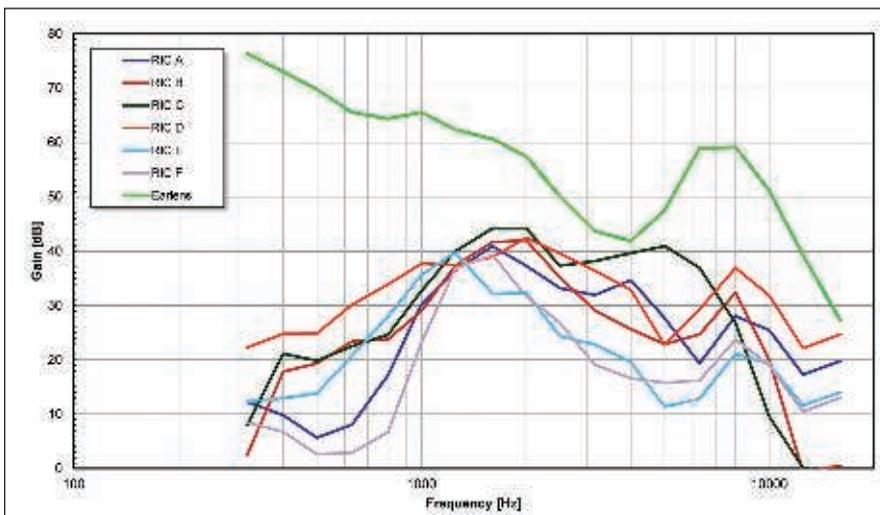Figure 9. Simulated insertion gain for open canal condition, 65 dB pink noise stimulus,1/3 octaves.

Figure 10. Maximum simulated insertion gain before feedback for open-fit canal, 65 dB speech noise stimulus,1/3 octaves.

	f1	f2
RIC A	970 Hz	4.6 kHz
RIC B	970 Hz	4.9 kHz
RIC C	910 Hz	3.9 kHz
RIC D	970 Hz	4.2 kHz
RIC E	730 Hz	4.3 kHz
RIC F	810 Hz	4.3 kHz
RIC Mean Bandwidth	890 Hz	4.4 kHz
Earlens	125 Hz	10 kHz

Table 1. Effective bandwidth of hearing instruments tested.

under the same "realistic" real-world use conditions. Therefore, a number of choices were made in order to fulfill this objective. For example, effective bandwidth was calculated from the OSPL using a speech input and a typical audiogram rather than from the ANSI S3.22/IEC 60118-7 specification data because Reference Test Gain is not a "real-use" condition. A sloping audiogram (also in the middle of the Earlens fitting range) was used as input to the fitting software because it is an appropriate profile to be fit with an open-fit RIC device—devices generally not recommended for low frequency hearing loss. Note that, even in a widely vented fitting, the Earlens can be used for flat and reverse-slope losses, as well as a low frequency loss up to 60 dB.

Proprietary fitting algorithms were used to program each device. Applying the same standard non-linear fitting rule (NAL-NL2) would have defeated the "system design" (integrated hardware and software) concept; this was also not easily facilitated in all fitting programs, nor is it common practice.

Insertion gain represents the effective gain delivered by the hearing device. The insertion gain response of the RIC devices did not appear to follow the audiogram or any known fitting rule. In fact, these responses appear reversed in slope to what is expected in the extended high frequencies (ie, more gain for increasing hearing loss). This is likely due to the inability of the devices to deliver gain at high frequencies, as gain is limited by the receiver, feedback, and/or the proprietary fitting algorithm.

A RIC device is limited in ability to provide output at low frequencies due to the open fitting. Low frequency gain would not be prescribed for the typical audiogram shown, but low frequency output would be valuable when streaming media—even for those with normal hearing in the low frequencies. For those who would desire to stream with low frequency output or for those who have a hearing profile

which would require low frequency gain, an occluded dome or earmold on a RIC would be necessary to deliver optimal low frequency sound quality, but this often comes with the perceptual trade-off of occlusion. Using real-ear verification and a non-proprietary fitting algorithm that provides targets into the extended high frequencies may boost the effective upper bandwidth. However, this effect is not usually significant, as those who routinely perform real-ear verification commonly report.

Effective bandwidth was significantly wider under real-world conditions for the Earlens device than for RIC devices. For the typical open-fit RIC device, the usable bandwidth for the input audiogram was 890 Hz to 4.4 kHz. In that bandwidth, high frequency speech and music information above 4.4 kHz may be inaudible. Likewise, low frequency information, such as vowel formants, may be inaudible, negatively affecting intelligibility and perceived naturalness of speech.

Bandwidth coverage for music is not optimal in the open-fit RIC devices; according to some definitions,[21] "high fidelity" requires a bandwidth of 40 Hz to 14 kHz. The Earlens bandwidth of 125 Hz to 10 kHz easily covers the speech bandwidth and approaches a high fidelity bandwidth for music while maintaining a non-occluded fitting.

Gain before feedback was determined band by band, but the responses were measured with each device stable (without feedback) at all frequencies. Feedback cancellation algorithms were disabled, as the maximum gain measurement was intended to measure the effect of physical acoustics (the feedback path from the receiver to the microphone in-situ). Maximum insertion gain before feedback for the RICs was 22-39 dB. The gain margin of the Earlens was 55 dB in the same bandwidth as the RICs. This large margin is due to the absence of a direct acoustic path between the microphone and the Tympanic Lens receiver. Feedback with the Earlens only occurs after the acoustic energy radiating from the tympanic membrane (in response to being driven by the Lens) passes through the widely vented fitting and reaches the microphone. Like a conventional air conduction device, the use of an adaptive feedback cancellation algorithm with the Earlens would similarly increase the gain margin.

Conclusion

The effective real-world bandwidth of RIC devices will vary based on hearing loss, acoustic configuration/venting, and the prescriptive fitting formula used. For the typical contemporary open-fit RIC device, this study revealed that the usable bandwidth before marked roll-off was approximately 890 Hz to 4.4 kHz. The gain before feedback varied by manufacturer, but was 31 dB on average. In contrast, the Earlens yielded a usable bandwidth of 125 Hz to 10 kHz, and a gain margin before feedback of 55 dB in the mid-band and up to 75 dB at low frequencies. With its high and low frequency extension, the ability to deliver gain at low frequencies in a widely vented fitting, and a high gain margin before feedback, the Earlens outperformed conventional open-fit air conduction hearing aids in these metrics and greatly improve treatment options for people with a wide range of hearing loss.

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