zōn™

with BluWave™ SP

In the Zōn: Excellence and Innovation in Hearing Instrument Design

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March 2008

Starkey®

Introduction

In recent years, there has been an increasing trend toward fitting BTE hearing aids, including receiver-in-canal (RIC) instruments. It is estimated that 51% of the hearing aids fitted in the U.S. in 2008 will be BTE instruments, rather than custom products (HIA, 2007). In a survey by Kochkin of 2500 hearing aid users, patients reported a desire for hearing aids that do not feedback (85%), fit comfortably (79%), and are less visible (52%) (Kochkin, 2005). These data support patient and practitioner demand for hearing instruments that are small and fit comfortably.

RIC products meet many consumer and professional demands. Such devices can be coupled to the ear canal using either an open-canal or closed earmold or stock earbud. The market share growth of behind-the-ear hearing aids has been driven largely by the increased use of open-canal fittings (Fabry, 2006). Modern open-canal instruments combine the acoustic benefits of an unoccluded ear with small size, comfort and cosmetic appeal. Together these features offer an attractive solution for people with mild-to-moderate, sloping hearing loss or a precipitous high-frequency loss.

In initiating the development of a RIC device, the design team adhered to the evidence-based design (EBD) principles that form the foundation of all Starkey design efforts. While EBD typically connotes involvement of numerous scientific disciplines – acoustics, psychoacoustics, audiology, digital signal processing, materials sciences and electrical, mechanical and software engineering – another important form of data collection involves systematic exploration of user and practitioner preferences. Beyond the published market data, further steps were taken to ensure that the resulting products clearly targeted the needs and preferences of end users and hearing professionals alike.

Starkey's development team investigated market trends and user and professional preferences with surveys and focus groups, consisting of hearing care professionals and patients. Interviews were held with current hearing aid users and self-identified future users, both men and women, from geographically diverse areas of the U.S., ranging in age from 65 to 85 years. These participants consistently expressed an interest in instruments that offer comfort; a secure, stable, yet unobtrusive fit on the ear; controls that are easy to reach and adjust; and overall ease of handling, especially for persons with limited manual dexterity. Hearing professionals expressed interest in Starkey developing a RIC product that would provide more gain without feedback, offer directional microphones, while being visually appealing to the patient. These comments clearly pointed to a need to address both the art of design and the science of sound to develop a new product that would excel in the competitive class of RIC instruments. The goal of the project was to design an instrument that was elegant, sophisticated, and, when presented, would convey an image that is technologically advanced.

In addition to input from patient and practitioner focus groups, the designers also sought input on skin tones, the physical makeup of the skin, and the impact of age on the skin and cartilage of the ear. They received guidance from Beverly Hills colorists on hair colors to identify colors that would be appreciated by patients who wanted the instrument to be invisible when placed on the ear. The Starkey development team combined the results of this extensive market research with ongoing research in numerous scientific disciplines – acoustics, audiology, digital signal processing, electrical engineering, materials sciences, mechanical engineering, psychoacoustics and software engineering – to create a device that would meet both the performance needs and the stylistic preferences of hearing aid wearers.

Introducing Zōn

With the introduction of Zōn, Starkey is raising the bar on RIC fittings. In the Zōn family of hearing instruments, Starkey offers a cosmetically appealing, compact, RIC hearing instrument with unparalleled performance and style. This paper describes the principles and operation of some of Zōn's most important features.

At the core of Zōn's acoustic performance is Starkey's new BluWave Signal Processing, a proprietary, optimized, operating system that controls the entire Zōn feature set. The BluWave SP operating system allocates resources and manages power by coordinating the many dynamic, interactive features of the Zōn product. Furthermore, as an open architecture, software-driven system, BluWave SP allows for upgrades in existing algorithms through firmware upgrades to the hearing aid chip. With the arrival of BluWave SP, the enhancement of hearing instrument features will no longer depend entirely on building a new circuit.

This paper will describe evidence from benchmarking research to give readers an understanding of how Zōn will improve their patients' rehabilitative success. Three of Zōn's key features are described, all of which address basic amplification goals of achieving optimal audibility and speech intelligibility:

- Active Feedback Intercept (AFI)
- Directional Speech Detector (DSD)
- Integrated Real Ear Measurement (IREM)

These features represent a subset of the total feature set of the Zōn product, managed by BluWave SP. The combination of acoustic benefits with appealing size, comfort and style are expected to guarantee successful outcomes with the Zōn product line (Figure 1) for patients and hearing professionals alike.

Figure 1. Starkey Zōn shown in each of the six available colors

RIC Overview

Zōn is a RIC product, a hearing aid style in which the receiver is separated from the body of the hearing instrument and placed in the wearer's ear canal. Receiver placement in the canal offers some advantages over conventional hearing aid design. The most obvious impact of moving the receiver out of the case is the potential for a smaller case and greater creativity in artistic aspects of its design. It is also possible that physical separation of the microphone and receiver may reduce feedback by minimizing structural feedback pathways within the hearing instrument (Ross & Cirmo, 1980). Finally, the RIC design allows the practitioner to exchange a receiver in the office, rather than sending the aid to the manufacturer for service.

The output of RIC instruments, including Zōn, can be delivered to the ear canal through either an open or a closed delivery system. The benefits of open-canal fittings have been well documented (Johnson, 2006; Mueller, 2006; Taylor, 2006).

In its open-canal configuration, the Zōn hearing instrument offers all the benefits of this popular coupling technique (Johnson, 2006; Mueller, 2006; Taylor, 2006). The occlusion effect is minimized. Low-frequency sounds bypass the hearing instrument altogether, providing a natural sound quality for users who do not need amplification in the low-frequency region. And the unoccluded ear canal retains its natural resonance characteristics, enhancing the response in the 2-3 kHz region and further enhancing sound quality (Mueller & Ricketts, 2006).

When used with a closed sound delivery system, Zōn offers an impressively wide fitting range for such a small, elegant instrument. By occluding the coupling to the ear, low frequencies are enhanced for those who need low-frequency amplification, allowing the instrument to fit a wider range of hearing losses than the open-canal configuration.

While the market has seen and responded to the benefits of modern RIC instruments, Zōn takes these benefits to a new level by controlling feedback, maintaining a stable, highly directional microphone response with proven efficacy and ensuring the most accurate frequency response for each individual ear. The following discussion will elaborate on Zōn's unique processing features.

Active Feedback Intercept (AFI)

Feedback, which for years has limited the capabilities of hearing aids (open-canal and conventional products alike), has met its match in Starkey's Active Feedback Intercept (AFI). First designed for Starkey's Destiny™ line of hearing instruments, AFI has been shown to control feedback more effectively than any competing feedback cancellation system. Now the performance of AFI in the Zōn has been benchmarked against leading receiver-in-the-canal products. Only the three top performing products are depicted in each figure throughout this document.

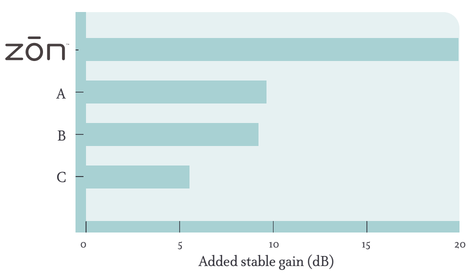

Figure 2. Added Stable gain of the Starkey Zōn and three competing products.

Laboratory evaluation of feedback cancellation performance was completed on all available competitive RIC products, using an established battery of tests (Merks et al., 2006), which quantifies added stable gain (ASG) as the difference between maximum stable gain (MSG) with the feedback canceller on and MSG with the feedback canceller off. The higher the ASG, the more benefit the patient can receive from the feedback cancellation. Each instrument was placed on KEMAR's right ear and subjected to the same evaluation procedure, which allows objective measurement of ASG with no ceiling effects created by reaching the maximum output of the instrument.

Figure 2 shows ASG for Starkey's Zōn and the three top performing competitive products, all with an open-canal fittings using each manufacturer's proprietary earbud. AFI in Zōn achieves 20 dB of ASG, well ahead of the competition. The 10 dB advantage of the Zōn product over the closest competition means that it will allow higher gain without feedback, thus accommodating a wider range of hearing losses and offering a greater safety margin from feedback in the field.

Two additional features of feedback cancellers were evaluated – the audibility of entrainment artifacts and the ability of the hearing aid to adapt to changes in the feedback path. This first measure specifically quantifies any distortions that arise from adaptive feedback cancellation techniques. The second assesses the ability of the algorithm to maintain a feedback-free output when the feedback path is changed by factors such as yawning or covering the ear with a phone. While one of the competing instruments tested revealed an unacceptable degree of entrainment artifact, the remaining instruments, including Zōn, handled entrainment well, creating a negligible difference in signal quality. Likewise, all competitive products performed within acceptable limits on the assessment of path change effects.

In addition to evaluating ASG in the laboratory with KEMAR, maximum stable gain (MSG) of Zōn and the competing RIC products was measured in the right ear of twenty subjects, with feedback cancellers on. MSG is defined as the maximum insertion gain that can be achieved without audible feedback oscillation. The only subject-selection criterion was that the participants' ear canals not be occluded by cerumen. Receivers of all instruments were placed in the canals without earbuds to ensure the most open fitting possible and avoid variability created by different earbud designs.

The instruments were programmed to linear gain, and adaptive features were disabled. The initialization procedure of each feedback cancellation algorithm was performed, and the feedback canceller was turned on. To determine MSG, gain was systematically increased in each available band in each instrument, beginning at the lowest frequency and proceeding to each successively higher frequency band. Gain was increased until feedback was detected or maximum output was reached. When feedback occurred, band gain was reduced to a stable level, just below the point of feedback. This sequence of gain adjustments by frequency continued until each channel reached its maximum stable gain or maximum available output.

At the completion of these adjustments, at the MSG limit, insertion gain as a function of frequency was measured with a Fonix 6500 real-ear measurement system, using conventional real-ear measurement procedures. Results for Zōn and its three closest competitors are shown in Figure 3. In the mid to high frequencies, MSG in Zōn exceeds that of the competition by an average of 8.5 dB, with a maximum difference of 13 dB. The gain shown here reinforces the class leading performance of the AFI in Zōn, in agreement with prior evaluations in Destiny (Banerjee, 2006; Merks et al., 2006).

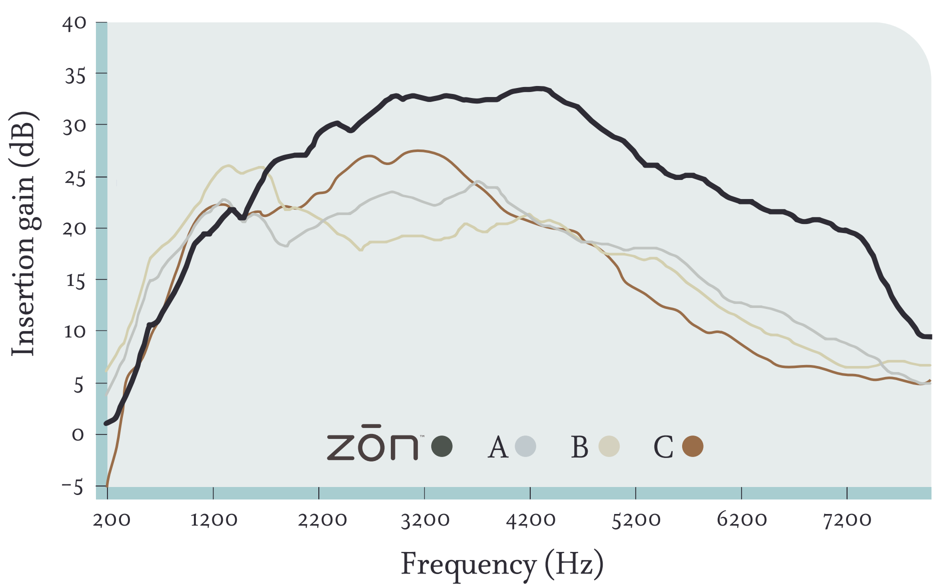

Figure 3. Mean insertion gain as a function of frequency for the Starkey Zōn and the three closest competitors.

Directional Speech Detector (DSD)

Directional microphones in hearing instruments offer the only proven means of improving signal-to-noise ratio and thus improving speech intelligibility in noise, without the use of external equipment (Ricketts, 2001). Incorporation of the best possible directional design, therefore, was an important goal in the Zōn development.

Starkey engineers designed the Directional Speech Detector (DSD) to maximize patient benefit in real-world conditions. For a detailed review of DSD's rationale and development, please refer to Yanz (2006). DSD uses a two-port single differential directional microphone, also referred to as an acoustic directional microphone, in combination with a second omnidirectional microphone to provide either manual or dynamic switching between omnidirectional and directional modes. This approach to directional processing provides a directivity index (DI) that is consistently high throughout the range of frequencies important to speech understanding. Additionally the use of a single directional microphone also eliminates the possibility of microphone drift that may occur in two-microphone directional systems (Ricketts & Dittberner, 2002), ensuring that the Zōn directional benefit will be maintained throughout the life of the product. DSD also offers dynamic switching between omni- and directional microphone modes. Seamless microphone switching is accomplished through a decision making algorithm that integrates multiple types of data – overall input level, omnidirectional and directional microphone outputs and signal-to-noise ratio – to optimize speech intelligibility and listening comfort, while maintaining a stable perceptual image.

Directivity in the free field. Table 1 provides horizontal plane, free-field DIs, measured in a sealed coupler, the data are averaged across 500, 1000, 2000, and 4000 Hz, for Zōn and the top three performing competing products. DI is a valuable measure in that it provides a single number that is representative of the attenuation provided by directional microphones. This attenuation may also be interpreted as *effective* SNR. In other words, the magnitude of DI is related to the amount of directional benefit a patient may experience (Ricketts, 2001).

	zōn	A	B	C
DI	5.76	4.84	4.38	4.34

Table 1. Average Free-field Directivity Index (DI) for the Zōn and the three closest performing competitors.

Directivity on KEMAR. Figure 4 shows DI as a function of frequency, recorded on a KEMAR manikin in an open-canal fitting with Starkey Zōn and the three top performing competing products. As expected, the DI quickly falls off below 1000 Hz for all products. A directional response cannot be obtained in a frequency region where there is no gain (Bentler, 2006). Thus, the lack of low-frequency directivity is the result of the basic open-canal design, the acoustics of which inherently roll off low-frequency gain. Throughout the key speech frequency range the directivity of all the evaluated instruments grows, with Zōn consistently achieving the highest DI versus its competition.

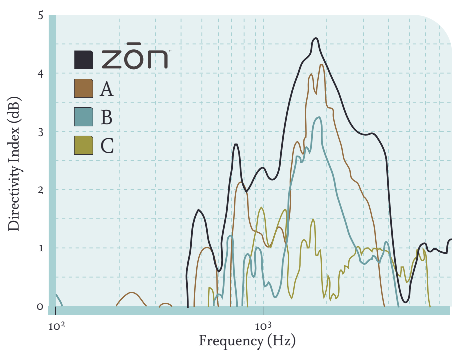

Figure 4. Directivity Index as a function of frequency for the Starkey Zōn and three competing RIC products.

Behavioral evaluation. To assess the directional benefit of DSD in Zōn, fourteen, hard of hearing participants with mild to moderately-severe hearing loss completed a task of speech recognition in noise using the Hearing in Noise Test (HINT) (Nilsson et al., 1994). Each listener was fit bilaterally with the Starkey Zōn to the prescriptive recommendations of a modified version of NAL-NL1 (Dillon, 1999), this version is available in the Inspire® OS 3.0 software as NAL-NL1*. Each subject was seated in the center of an 8-loudspeaker array, with speech coming only from the loudspeaker at 0 degrees azimuth. The remaining 7 speakers generated a noise field of uncorrelated speech-shaped noise surrounding the listener, as indicated in Figure 5. Signal presentation began at a level of -10 dB SNR with the speech stimulus at 55 dB SPL. Threshold was defined as the SNR obtained after the presentation of twenty sentences.

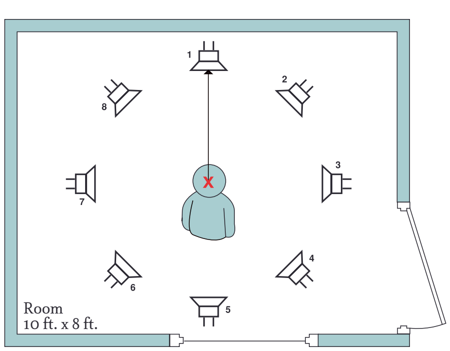

Figure 5. An 8-loudspeaker array was used for HINT testing. The speech loudspeaker is positioned at 0 degrees azimuth.

A one-way repeated measures analysis of variance revealed a significant main effect of listening condition, $F(1,2) = 25.6$, $p = .001$. A follow up analysis using a Bonferroni t-test was completed across each combination of listening conditions. These analyses showed a significant increase in performance between the unaided and DSD conditions ($p<.001$) and the omnidirectional and DSD conditions ($p<.001$). Figure 6 shows mean performance on the HINT as a function of unaided, omnidirectional, and directional listening conditions. Though not significant, average performance improved between the unaided and omnidirectional listening conditions. This increase in performance is in contrast to previous studies that have observed a decrease in speech understanding in noise between unaided and omnidirectional listening conditions (Ricketts & Dhar, 1999). With 3.1 dB of improvement in performance threshold in the directional mode as

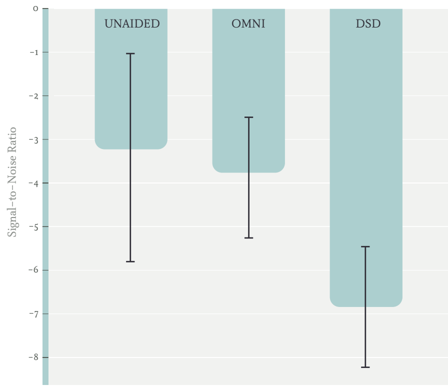

Figure 6. Mean HINT thresholds measured under three listening conditions: unaided, aided with Zōn in omnidirectional mode and aided with Zōn in directional mode. Error bars represent +/– 1 standard deviation.

Figure 7. Starkey Zōn .7 with Integrated Real Ear Measurement comes "Real Ear Ready" from the manufacturer.

compared to omnidirectional, it is apparent that even in an open-fit configuration, DSD in the Zōn provides listeners with significant improvements to speech understanding in noise.

From the discussed clinical and laboratory performance measures, the benefits of DSD in Zōn are readily apparent. Zōn provides class-leading DIs in free-field and in-situ evaluation, leading to improved speech understanding in noise. And with the stability offered by a single differential directional microphone, the possibility of losing directivity due to microphone drift is eliminated.

Integrated Real Ear Measurement (IREM)

The clinical application of real-ear measurement is used to verify the appropriateness of a hearing aid fitting and considered a standard of best practice as detailed by the American Academy of Audiology (Abrams et al., 2006). Unfortunately, the majority of hearing professionals do not perform real-ear measures as part of their routine practice (Strom, 2006; Kirkwood, 2006). In the absence of formal research into the reasons for its disuse, conversations with hearing professionals suggest that they attribute it generally to cost of equipment, time demands of a busy practice and the perceived cumbersomeness of the measurements. Furthermore, some have inaccurately concluded that real-ear verification of a fitting is not possible in open-canal instruments, due to the contribution of the direct signal that bypasses the hearing aid. In fact, real-ear measurement is just as valid in an open-canal fitting as in a conventional fitting, provided some simple steps are taken in setting up the equipment (Mueller & Ricketts, 2006).

Zōn .7, the flagship of this new line, offers real-ear measurement integrated into the hearing aid itself, reducing our reliance on external equipment (Figure 7). Through the development of BluWave SP, Integrated Real Ear Measurement (IREM), first developed for the Destiny 1600, is being implemented in a premier RIC device.

IREM in the Zōn .7 automatically adjusts the hearing instrument response based on the measured acoustic characteristics of each patient's ear, thereby improving the accuracy of the initial fit to target. As a result, the patient will have better audibility over the frequency range needed for his/her hearing loss. Failure to achieve audibility, at the start of a hearing instrument fitting, may ultimately lead to reduced benefit and increased dissatisfaction.

Figure 8, provides 30 real-ear to coupler differences (RECDs) as measured through Zōn .7. From these data it's apparent that an individual RECD may vary from one person to the next. In the absence of collecting individual RECD data average RECD values must be substituted and the accuracy of the initial fit cannot be determined. IREM in Zōn .7 automatically collects individual RECDs and applies them to the fitting within Inspire OS 3.0. Incorporating the measured RECD into Inspire OS 3.0 ensures that the graphical display of the hearing aid response on the computer screen is an appropriate representation of the hearing aid output in the patient's ear.

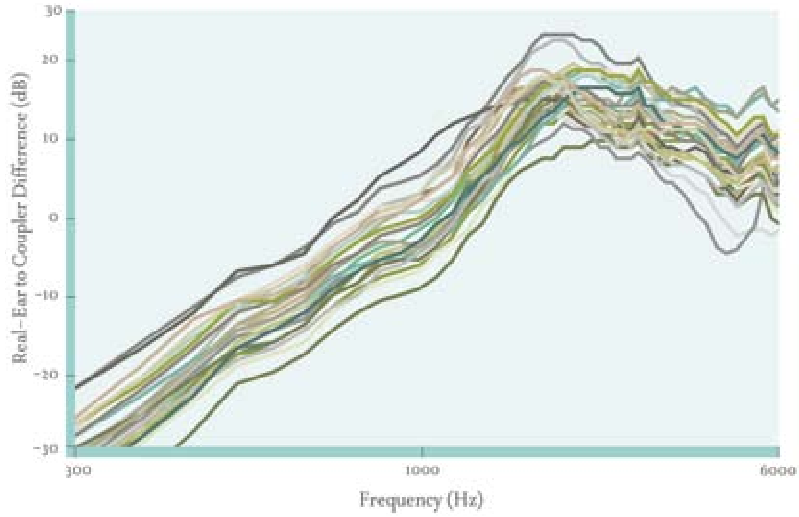

Figure 8. Thirty RECDs as a function of frequency, as measured using Integrated Real Ear Measurement in Zōn .7.

The measurement of RECD in Zōn .7 is not only accurate but repeatable. To evaluate the test-retest reliability of IREM in Zōn, an initial RECD was measured, and then the probe tube and hearing aid were removed and reinserted prior to repeating the RECD measurement on 29 ears. Consistent probe tube placement, important to measurement accuracy, is facilitated by tic marks on the probe tube, allowing positioning relative to either the intra-tragal notch or the canal aperture. The tip of the probe tube was positioned 5 mm beyond the tip of the receiver. Test-retest reliability is displayed in Figure 9 as the absolute difference between the two RECD measurements.

Integrated Real Ear Measurement capability of Zōn .7 eliminates the barriers of cost, additional time and equipment, which have prevented hearing professionals from performing real-ear verification. Now practitioners can be comfortable knowing that they are beginning each fitting with a close match to their selected target, helping to ensure audibility across the frequency range needed for each hearing loss. By virtue of that close fit, the need for further fine-tuning should be reduced, and since each individual real ear response is stored inside each hearing aid, the IREM only needs to be run a single time. With the IREM procedure, one can expect that once these data are stored, the graphic displays in the Inspire OS 3.0 software reflect an accurate representation of the hearing aid response in the ear canal. The displays are updated with any adjustments made on any subsequent visits.

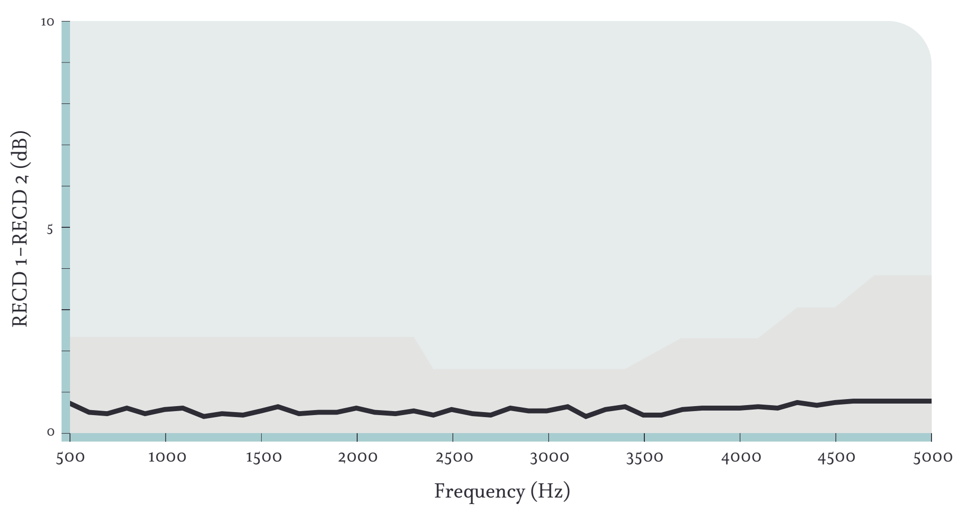

Figure 9. Mean difference between two RECDs as recorded using Integrated Real Ear Measurement in Starkey Zōn .7 as a function of frequency for 29 ears. The shaded area represents the range of variability in this measurement.

Summary

Evidence-based design principles are at the core of every Starkey product development effort. In the case of the Zōn receiver-in-the-canal device, developers brought two categories of evidence to bear on design decisions. First, researchers in multiple scientific disciplines gathered data on efficacy and effectiveness of signal processing algorithms to optimize audibility, intelligibility, comfort and sound quality. Second, market researchers helped guide the design effort with published market studies and focus groups of hearing professionals and end users of hearing technology. The goal was straightforward, to determine what our customers wanted simply by asking them.

The result of this dual approach to product design is a RIC instrument that offers a unique combination of style and performance. The case was designed for comfort, a secure fit on the ear, ease of use and an elegant appearance. The processing algorithms on the inside put this stylish product in a performance class of its own.

Active Feedback Intercept in Zōn offers class-leading gain margins without feedback or artifacts. No other RIC product is as effective in controlling feedback. The Directional Speech Detector has been shown to produce a high directivity index in a stable, low-noise design, with supporting data from engineering laboratory assessments and clinical research. The end user will experience the goal of improved speech understanding in noise. And Integrated Real Ear Measurement, now available for the first time in a RIC product, promises unparalleled accuracy in fitting to a prescriptive target, without the added cost and time requirements of conventional real-ear equipment. The result will be to achieve good audibility over the needed frequency range more efficiently than ever before.

The scope of this paper does not include all of the features in Zōn hearing instruments or in the Inspire OS 3.0 software that programs them. Rather, it provides an overview of the most salient features that make Zōn an exceptional RIC hearing instrument. For a full understanding of the entire package that Zōn offers, the reader is encouraged to contact their Starkey Representative or visit StarkeyPro.com.

Acknowledgements

We would like to thank Weili Lin, Ivo Merks, Harikrishna Natarajan, Laurel Olson, Chad Parrish, Justyn Pisa, and Aaron Schroeder for developing the studies and completing the collection of data that support the information provided in this document.

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