Published in final edited form as:

Int J Audiol. 2015 February ; 54(2): 96–105. doi:10.3109/14992027.2014.941074.

Exploration of stimulus-frequency otoacoustic emission suppression tuning in hearing-impaired listeners

Karolina K. Charaziak, Pamela E. Souza, and Jonathan H. Siegel

The Roxelyn and Richard Pepper Department of Communication Sciences and Disorders, School of Communication, Northwestern University, Evanston, USA

Abstract

Objective—Otoacoustic emissions (OAEs) can provide useful measures of tuning of auditory filters. We previously established that stimulus-frequency (SF) OAE suppression tuning curves (STCs) reflect major features of behavioral tuning (psychophysical tuning curves, PTCs) in normally-hearing listeners. Here, we aim to evaluate whether SFOAE STCs reflect changes in PTC tuning in cases of abnormal hearing.

Design—PTCs and SFOAE STCs were obtained at 1 kHz and/or 4 kHz probe frequencies. For exploratory purposes, we collected SFOAEs measured across a wide frequency range and contrasted them to commonly measured distortion product (DP) OAEs.

Study sample—Thirteen listeners with varying degrees of sensorineural hearing loss.

Results—Except for a few listeners with the most hearing loss, the listeners had normal/nearly normal PTCs. However, attempts to record SFOAE STCs in hearing-impaired listeners were challenging and sometimes unsuccessful due to the high level of noise at the SFOAE frequency, which is not a factor for DPOAEs. In cases of successful measurements of SFOAE STCs there was a large variability in agreement between SFOAE STC and PTC tuning.

Conclusions—These results indicate that SFOAE STCs cannot substitute for PTCs in cases of abnormal hearing, at least with the paradigm adopted in this study.

Keywords

Frequency selectivity; otoacoustic emissions; psychophysical tuning curve; suppression tuning curve; hearing impairment

The cochlea is an unusual sensory organ which not only signals received acoustic energy to the brain but also emits sounds back to the ear canal (otoacoustic emissions) where they can be recorded with a sensitive microphone (Kemp, 1978). In a way otoacoustic emissions (OAEs) can be viewed as a by-product of cochlear processing (specifically outer hair cell function) meaning that they demonstrate a promise to serve as a non-invasive tool for assessment of cochlear functional status (for a recent review see Kemp, 2007). Since their

discovery in 1978, there have been many attempts to extend the clinical utility of OAEs beyond simple hearing screening by trying to relate them to specific cochlear functions (e.g. the tuning of cochlear filters that underlie frequency selectivity; Johnson et al, 2007). As a part of those attempts, in a previous study we assessed the applicability of stimulus-frequency (SF) OAEs to predict behaviorally assessed tuning in normally-hearing listeners (Charaziak et al, 2013). In this study, we aim to evaluate whether SFOAEs could reflect possible degradation of frequency selective filtering processes in cases of sensorineural hearing loss.

OAEs can occur spontaneously or can be evoked with external sounds. The most commonly studied OAEs are evoked with a pair of tones (distortion product, DPOAEs) or with transient stimuli (transient evoked, TEOAEs), whereas emissions evoked with a single tone (stimulus-frequency, SFOAEs) have gained much less attention in the literature. The reason for that lies in the measurement procedures. TEOAEs and DPOAEs can be separated from the evoking stimulus pressure using the simple methods of time and frequency analysis, respectively. In contrast, SFOAEs cannot be measured directly because they overlap with the evoking tone in both time and frequency and more complex analysis routines have to be employed (see Kalluri & Shera, 2007 for measurement method comparisons). On the other hand, SFOAEs may be superior to other evoked OAEs for assessment of cochlear functions such as frequency selectivity due to the extremely frequency-limited characteristics of the evoking stimulus and/or due to the expected simple mechanism of SFOAE generation in the cochlea (Zweig & Shera, 1995; Shera & Guinan, 1999).

Frequency selectivity is one of the most basic features of the auditory system that is derived primarily from the cochlea where outer hair cells act to sharpen tuning of the mechanical responses by actively generating forces that enhance resonances of the basilar membrane (for review see Robles & Ruggero, 2001). Frequency selectivity is often defined as an ability of the auditory system to filter one stimulus out from others on the basis of frequency and it has been shown to be important for perceiving complex sounds such as speech in noise (reviewed in Moore, 2008). Not surprisingly then, it has been suggested that including frequency selectivity measures in the clinical test battery may improve diagnostics and counseling (e.g. Zwicker & Schorn, 1978; Robinson et al, 2007), particularly because there is little correlation between behaviorally measured hearing sensitivity and frequency selectivity (e.g. Moore et al, 1999).

While in laboratory animals cochlear frequency selectivity can be directly assessed with recordings from the basilar membrane or auditory nerve fibers (i.e. single-tone tuning curves), such procedures cannot be applied to humans due to their invasive nature. Thus, behavioral methods are commonly employed to estimate frequency selectivity in humans, such as measurements of psychophysical tuning curves (PTCs). To obtain a PTC, the threshold of audibility for a low-level probe tone in the presence of a masker (another tone or a band of noise) is established across different masker frequencies, forming a characteristic V-shaped curve (Zwicker, 1974). Using an analogous procedure, an OAE suppression tuning curve (STC) can be measured, where a predefined change in OAE amplitude (i.e. suppression criterion) is tracked across different suppressor frequencies. Because behavioral methods cannot be applied in certain populations (e.g. newborns) it

would be of interest to establish whether objective and non-invasive OAE STCs could be used as an alternative measure of tuning.

It has been shown that OAE STCs qualitatively reflect features of behavioral tuning in humans (e.g. Kemp & Chum, 1980; Zurek, 1981; Zwicker & Wesel, 1990; Harris et al, 1992). However, quantitative comparisons showed that commonly studied DPOAE STCs tend to indicate broader tuning (i.e. poorer frequency selectivity) than anticipated based on the behavioral tests, while SFOAE STCs seem to agree better with behavioral estimates of tuning, at least in normally-hearing listeners (reviewed in Johnson et al, 2007; also see Keefe et al, 2008; Charaziak et al, 2013). Further support for the use of SFOAE STCs as a measure of frequency selectivity comes from a study in mice where SFOAE STCs were as sharply tuned as auditory nerve fiber tuning curves (Cheatham et al, 2011).

The question that remains to be answered is whether SFOAE STCs can reflect changes in frequency selectivity (e.g. due to hearing loss) at the individual level. Although we previously found a good agreement between average SFOAE STCs and PTCs in normally-hearing listeners, within an individual there was considerable variability in the degree of agreement (Charaziak et al, 2013). One interpretation of this result is that SFOAE STCs are not useful for predicting an individual's frequency selectivity. On the other hand, the small variability in PTC tuning observed across listeners may have prevented us from detecting a correlation between PTCs and SFOAE STCs. To further assess the clinical applicability of SFOAE STCs to serve as an objective and non-invasive measure of frequency selectivity, we tested listeners with different degrees of sensorineural hearing loss that are more likely to show deficiencies in the frequency selective filtering process. Thus, we aim to establish whether SFOAE STCs can reflect features of PTCs in cases of subjects with abnormal hearing thresholds in quiet.

Materials and Methods

Subjects

Thirteen listeners (21–67 years old, six females) with varying degree of hearing loss (shown in Figure 1) participated in the study. All listeners had normal middle-ear status (assessed via 0.226-kHz tympanometry; Interacoustics, AA220; Margolis & Heller, 1987), normal results of otoscopic examination (i.e. clear ear canals and normal appearance of the eardrum), and sensorineural hearing loss at 1 and/or 4 kHz in the ear chosen for testing (based on the degree of hearing loss or at random for symmetric hearing losses). The air-conduction hearing thresholds (in dB sound pressure level, SPL) were assessed with a modified Békésy tracking procedure at octave frequencies from 0.125–8 kHz (Lee et al, 2012; Charaziak et al, 2013). To assess the degree of hearing loss the listeners' hearing thresholds in quiet were referenced to mean hearing thresholds of normally-hearing young adults (22–35 years old) measured with the same methods (Lee et al, 2012). Based on the degree of hearing loss (HL) at 1 kHz and 4 kHz the listeners were assigned to groups (<10 dB HL, 10–25 dB HL, 25–45 dB HL) separately at each frequency (see the box in Figure 1). The four listeners having thresholds <45 dB HL at 4 kHz were not tested further at this frequency.

The study was approved by the Northwestern University Institutional Review Board and listeners were paid an hourly rate for their participation.

Instrumentation

All measurements were carried out using the same equipment and procedures as described in detail elsewhere (Charaziak et al, 2013). In short, the listeners were seated comfortably inside a sound-attenuating booth with a tip of an OAE probe (Etymotic Research ER-10B+) placed in the ear canal. The sounds were delivered via two modified sound source transducers (MB Quart 13.01 HX) coupled to the OAE probe. The tonal stimuli and the suppressors/maskers were presented monaurally through separate sound sources to minimize nonlinear stimulus interactions. The signals were generated and controlled with software (see Procedures) using a 24-bit audio interface (Echo Audio Gina3G). The sample rate was set at either 44.1 kHz or 88.2 kHz (buffer sizes 8192 or 4096 points) depending on the software. The measured stimulus and OAE signals were compensated for the microphone transfer function. The stimulus level at the eardrum was controlled using the depth-compensated ear simulator method (Lee et al, 2012).

Procedures

Data were usually collected within five 2-hour sessions. Typically, a SFOAE STC was collected within 10–15 minutes and a PTC within 4 minutes.

Psychophysical tuning curves

The PTCs were collected with the so called “fast” method (Sik et al, 2005; Charaziak et al, 2012, 2013). The gated tonal probe, f_{probe} (500-ms including 25 rise/fall times, repetition period of 200 ms), fixed in frequency (as used for SFOAE STC measurements described below) and level (10 dB SL), was presented simultaneously with a narrowband masker (0.2 or 0.32 kHz wide, for 1 and 4 kHz probes, respectively). The masker level was controlled by the subject via a button, as in Békésy audiometry, while the masker center frequency changed continuously in time (over a $0.5f_{probe}$ to $2f_{probe}$ range) from low to high (upward sweep) or from high to low frequencies (downward sweep; for details of masker synthesis see Charaziak et al, 2013). Listeners were instructed to press a button when the tonal probe was audible and to release the button when the tone became inaudible; the level of the noise was increased/decreased at fixed rate (4 dB/s) in 0.5 dB steps (maximum level: 90 dB SPL). To allow the listener to become familiar with the procedure the starting masker level was always set below the probe level and the masker center frequency was held constant until four reversal points were obtained. The points at which the button was pressed or released were recorded, producing a tracking record of masker levels as they crossed just below/above the masked threshold for the probe as a function of the masker center frequency. The raw-PTCs were smoothed with the LOESS algorithm with a smoothing parameter set at 0.25 or 0.3 to extract the masker levels necessary to just mask the probe across the range of masker center frequencies (Charaziak et al, 2012, 2013). The probe frequency/noise sweep direction conditions (four in total) were presented in random order. The subjects were given a 10–15 minute training block prior to data collection.

SFOAE recordings

For all measurements, SFOAE residuals were calculated as the difference between the averaged responses to the probe tone alone and to the probe tone in the presence of a suppressor tone (two repetitions of each, stored in separate buffers); the resulting waveform was analysed with a fast Fourier transform to obtain the SFOAE residual (i.e. the suppressed part of the total SFOAE). The noise level was estimated at the probe frequency from the spectrum of the difference between time-domain sub-averages stored in separate buffers. Trials demonstrating noise levels exceeding a predefined noise rejection criterion (see below) were repeated automatically.

Tuning curves were obtained at nominal probe frequencies of 1 and 4 kHz. Due to the presence of SFOAE fine-structure (variation in SFOAE amplitude with frequency; e.g. Kemp & Chum, 1980), the actual (optimal) probe frequencies (f_{probe}) were selected as those evoking the highest SFOAE levels (of at least -6 dB SPL with signal-to-noise ratio, SNR ≥ 6 dB) within ± 0.1 kHz of 1 kHz and within ± 0.2 kHz of 4 kHz. The f_{probe} was determined based on SFOAE fine-structure measurements from 0.8117 kHz to 1.1843 kHz (0.0215 kHz steps) and from 3.6822 kHz to 4.2851 kHz (0.0431 kHz steps) with the probe level fixed at 40 dB SPL and 50 dB SPL, respectively, with the suppressor always fixed at 0.0431 kHz below the probe frequency at 65 dB SPL. The measurements were repeated at high probe levels (60 and 65 dB SPL, respectively; the suppressor level was increased to 75 dB SPL) if the lower level measurements did not have sufficient SNR to identify an optimal f_{probe} for SFOAE STC testing. The f_{probe} selected for each listener are listed in Table 1 and Table 2, together with hearing thresholds and SFOAE levels estimated from SFOAE input-output (IO) functions at f_{probe} . The SFOAE IO was obtained for probe levels from 10 to 70 dB SPL (in 5-dB steps), with suppressor fixed 0.0431 kHz below f_{probe} at 75 dB SPL. For such suppressor conditions, nearly complete or complete suppression is expected so that the measured SFOAE residual probably accurately represents the total SFOAE (Brass & Kemp, 1993; Keefe et al, 2008). The SFOAE residuals at 10, 20, and 30 dB SL were estimated (Table 1, Table 2) using cubic spline interpolation of SFOAE IO points with SNR < 6 dB to evaluate a range of possible SFOAE STC criteria at each SL (see below). For simplicity, when referring to the data we ignored the individual differences in f_{probe} and refer to 1-kHz and 4-kHz curves.

The SFOAE STCs were measured as iso-residual curves for as many as three suppression (residual) criteria (-6 , 0, and 6 dB SPL) as a function of suppressor frequency for probe levels of 10, 20, and 30 dB SL. For brevity, SFOAE STCs collected for a given combination of conditions will be identified as criterion/probe level STC, e.g. $-6/10$ SFOAE STC for an STC collected for a -6 dB SPL criterion at a probe level of 10 dB SL. The 25–45 dB HL group was not tested with 30 dB SL probe levels due to insufficient dynamic range to measure tuning. The suppressor level was limited to 85 dB SPL, which commonly prevented reaching the criterion response for 30 dB SL probes for these listeners. For each probe level and suppressor frequency, the suppressor level was varied automatically using a tracking procedure until the SFOAE residual was within ± 1 dB of the residual criterion. The suppressor frequency was varied from $0.4f_{\text{probe}}$ to $2.1f_{\text{probe}}$ with a resolution of 5 points/octave and with increased resolution to 15 points/octave in the range from $0.9f_{\text{probe}}$ to

$1.4f_{\text{probe}}$. Data collection was automatically terminated when the suppressor level reached 85 dB SPL, when no response meeting the threshold criterion was found in 15–20 attempts or when the noise level exceeded a predefined noise rejection criterion in four consecutive attempts. The noise rejection criterion was typically set at –10 dB SPL and raised to 0 dB SPL in cases of noisy recordings (note: the noise criterion was always at least 6 dB below the residual criterion). The necessity of increasing the noise rejection criterion was related to the increased noise levels observed for higher probe levels (e.g. Schairer & Keefe, 2005).

To assess how well SFOAE STC tuning reflected features of the corresponding PTC, we calculated a ratio of the SFOAE STC width (measured 10 dB above its tip across the widest range ignoring any irregularities in thresholds, e.g. double tips, BW10) to the individual's PTC width (average BW10 for upward- and downward-sweep PTCs) referred here as the BW10 ratio.

Supplementary OAE measurements

Because the SFOAEs are relatively unexplored in listeners with hearing loss, as compared DPOAEs for example, we included additional measurements in the test protocol that were not essential for obtaining tuning curves but were helpful in interpreting some of the results. The goal was to understand better how SFOAE levels change with frequency over a wider range than initially included (around 1 and 4 kHz) and compare them to DPOAE levels. Such comparisons may provide insights into which OAE test may be more applicable for evaluating hearing-impaired listeners. The wide-range SFOAEs were measured from 0.495 to 7.988 kHz (in 0.0643 kHz steps) with the probe level fixed at 60 dB SPL and the suppressor fixed at 75 dB SPL, 0.0431 kHz below the probe frequency. The DPOAEs were measured as the response to stimulation with a pair of tones (f_1 and f_2 , $f_2/f_1 = 1.2$, f_2 varied from 0.479 to 8.333 kHz with resolution of 10 points/octave) at the intermodulation-distortion frequency $2f_1 - f_2$. We did not attempt to optimize the levels of two-tone stimuli to find the highest DPOAE levels (e.g. Johnson et al, 2006) because our focus was to evaluate DPOAEs evoked with stimuli similar in level to those used in SFOAE measurements. Thus DPOAEs were measured for probe levels of $L_1 = L_2 = 60$ dB SPL, but also at higher probe levels ($L_1 = L_2 = 75$ dB SPL).

Spontaneous (S) OAEs may interfere with external signals that could potentially influence the shapes of PTCs and OAE STCs (e.g. Martin et al, 1988; Baiduc et al, 2014). We screened all subjects for the presence of SOAEs but none were detected (see Charaziak et al, 2013 for the measurement procedures).

Results and Discussion

We first discuss the PTC data to assess the range of behavioral tuning properties in our sample. Next, we discuss the SFOAE IO functions to evaluate the potential for SFOAE STC measurements in listeners with hearing loss. Third we focus on SFOAE STCs and their relation to PTCs. Lastly we discuss the supplementary OAE measurements in light of future directions in using OAEs to assess frequency selectivity. Even though the focus of this study was to evaluate tuning properties in listeners with sensorineural hearing loss we also

collected data for a few listeners with normal hearing (<10 dB HL) at 1 kHz (see Figure 1) for comparison with previous results (Charaziak et al, 2013).

Psychophysical tuning curves

Simultaneous-masked fast-PTCs were collected for upward- and downward-sweep maskers at probe levels of 10 dB SL (except for listener kc27 for whom only the upward-sweep PTC was available). The bandwidths of PTCs as well as examples of individual PTCs obtained for listeners with varying degrees of hearing loss are shown in Figure 2 and Figure 3, respectively.

For the <10 dB HL group all 1-kHz PTCs were “V” shaped, with “tips” at the minimum masker level near f_{probe} , and as sharply tuned as PTCs reported previously for normally-hearing listeners as shown in Figure 2, A (black triangles vs. numbers within the light grey box). For the 10–25 dB HL group, PTCs at both 1 and 4 kHz also demonstrated narrow-band characteristics with tips tuned to the masker frequency of the f_{probe} and sharpness of tuning similar to PTCs obtained in normally-hearing listeners (Figure 2; numbers within the intermediate-shaded grey box), despite the observation that the tips of the tuning curves were slightly elevated (Figure 3, A, B). At 1 kHz all listeners from the 25–45 dB HL group appeared to have impaired frequency selectivity, demonstrated by broader than normal PTCs as shown in Figure 2, A (numbers within the darkest grey box) and Figure 3, C. At 4 kHz only three out of eight listeners from the 25–45 dB HL group demonstrated broader than normal PTCs, as is apparent in Figure 2, B (numbers within the darkest grey box) and Figure 3, D. The fact that the majority of the 25–45 dB HL listeners did not seem to have impaired frequency selectivity at 4 kHz is not unexpected. For instance Moore et al (1999) reported that the width of auditory filters showed little variation for listeners with hearing thresholds of 40 dB HL and better. It is possible that the etiology of the hearing loss differentiates the 25–45 dB HL listeners with considerably broader tuning at 4 kHz is (e.g. more severely impaired outer hair cell function than in the other cases). These results again emphasize the need to evaluate frequency selectivity on an individual basis, since listeners with similar hearing loss can demonstrate very different tuning properties.

The decreased sharpness of tuning observed in some cases of the 25–45 dB HL listeners may also reflect the necessity of using higher probe levels (in dB SPL) as compared to listeners with less hearing loss. To evaluate the effect of the probe level on features of PTCs we tested two listeners at additional probe levels of 20 and 30 dB SL at 1 kHz (Figure 2, A; listeners kc33 and 35, numbers connected with white dotted lines). While for listener kc33 the PTC broadened progressively with increasing probe level, there was no clear trend for the other one (e.g. Stelmachowicz & Jesteadt, 1984). Importantly, PTCs of the 10–25 dB HL listeners were still considerably more narrow than PTCs of the 25–45 dB HL listeners when compared at equal probe SPL. This result indicates that the broadening of PTCs in the latter group relates to impaired hearing function rather than probe level.

SFOAE input-output functions

Prior to SFOAE STC collection we obtained SFOAE IO functions at f_{probe} to evaluate a range of possible SFOAE STC criteria at each probe level. For the 10 dB SL probes, most of

the listeners (86%) had SFOAE residuals of -6 dB SPL or higher, indicating the potential for measuring SFOAE STCs for at least one (-6 dB SPL) criterion (see Tables 1 and 2). While the SFOAE residuals could be extracted for higher probe levels for listeners with hearing thresholds better than 25 dB HL, this was not often possible for the 25–45 dB HL listeners, due to either limited SFOAE IO measurement range (see Procedures) or too poor SNR.

We compare median SFOAE IO functions for different HL groups at 1 kHz (Figure 4, A–C) and 4 kHz (Figure 4, D). For the 1-kHz probe the 10–25 dB HL listeners had smaller SFOAE levels than <10 dB HL listeners when compared at equivalent probe SPL, even though both of these groups would have been considered within the limits of clinically “normal hearing”. This difference seems to be meaningful despite the small sample size in the <10 dB HL group, as the median SFOAE IO function obtained in that group (Figure 4, A) is in good agreement with the median SFOAE IO function obtained in a larger group of listeners with similar hearing levels (e.g. Schairer & Keefe, 2005). A similar decrease in OAE level as threshold increased up to 20 dB HL has been previously observed for DPOAEs (Dorn et al, 1998). In contrast, median SFOAE levels at 1 kHz were very similar for the 10–25 dB HL group (B) and the 25–45 dB HL group (C) when compared at equivalent probe SPL. Thus, there was no consistent drop in SFOAE levels with increasing hearing threshold, contrary to results obtained in a larger population (Ellison Keefe, 2005). For the 4-kHz probes it was difficult to evaluate how the median SFOAE IO function changed across HL groups due to an insufficient number of listeners in the <25 dB HL groups. The 4 kHz SFOAE IO function for the 25–45 dB HL group was shifted towards the right as compared to the 1 kHz data (Figure 4, C vs. D), indicating that to obtain a similar SFOAE residual level at 4 kHz the probe levels (in dB SPL) had to be higher by roughly 10 dB as compared to 1 kHz SFOAEs. This shift may reflect the fact that at 4 kHz these listeners had hearing threshold SPLs that were 10 dB higher on average (compare the last rows of Table 1 and Table 2). For the four listeners who had too much hearing loss to be included in the study (<45 dB HL) the median SFOAE IO function was embedded in the noise (data not shown) indicating no potential for SFOAE STC measurements.

Increasing the probe level led not only to a proportional increase in the SFOAE level but also to an increase in the noise at the SFOAE frequency for probe levels of 50 dB SPL and higher (so called “on-band” noise; Figure 4, grey dashed lines). The presence of on-band SFOAE noise in normally-hearing ears and ears with cochlear implants that is absent in an ear simulator suggests it is biological in origin. One possible origin of on-band noise is small changes in the middle-ear transmission due to fluctuations in the tone of middle-ear muscles (e.g. Schairer & Keefe, 2005).

SFOAE STCs and their relation to behavioral tuning

The <10 dB HL group—It was possible to measure SFOAE STCs at the 1-kHz probe frequency for all the listeners with thresholds <10 dB HL. In total we collected 16 SFOAE STCs that had similar attributes as SFOAE STCs described previously for normally-hearing listeners (Charaziak et al, 2013), thus these data are not discussed here in more detail. However, we could not obtain SFOAE STCs at a criterion of -6 dB SPL for the 20 and 30

dB SL probe levels in listeners kc31 and kc36 due to excessive noise above a predefined noise rejection criterion (i.e. insufficient SNR). There was considerable inconsistency in the success in predicting an individual's PTC tuning from their SFOAE STC, as the BW10 ratios ranged from 0.25 to 2.57. This was due to the large variability in the shapes of SFOAE STCs that we reported previously (see Figure 11 in Charaziak et al, 2013).

The 10–25 dB HL group—At 1 kHz the SFOAE levels obtained in the 10–25 dB HL group were considerably lower than in the <10 dB HL group when evaluated at the same probe SPL (Figure 4, A, B). Equalizing the probe levels *re* individual threshold (SL) made the SFOAE levels almost indistinguishable between the two groups at 10, 20, and 30 dB SL (Table 1). Thus, it was expected that SFOAE STCs should be as readily measurable in the 10–25 dB HL group for most conditions as they are for normally-hearing listeners. However, at 1 kHz we could not obtain any reliable SFOAE STCs for three (kc30, 37, and 39) of seven listeners due to high noise levels and inconsistent responses (i.e. non-monotonic variation in SFOAE residual level with varied suppressor level). Even though we encountered similar difficulties with obtaining SFOAE STCs for the remaining listeners, we were able to measure SFOAE STCs for 18 of 24 possible conditions (kc42, 41, 33, and 35). Examples of SFOAE STCs obtained across different conditions (the legend) are shown in Figure 5, A, for one listener together with his PTCs (black dashed lines). In this case the SFOAE STCs were roughly “V” shaped and demonstrated features of SFOAE STCs of normally-hearing listeners: tuning to a frequency $< f_{\text{probe}}$, upward shift of the whole STC with either increasing residual criterion (at fixed probe level, lighter vs. darker shades of grey) or with decreasing probe level (at fixed criterion, different line styles of the same grey color; Keefe et al, 2008, Charaziak et al, 2013). Even though the BW10s of some SFOAE STCs were similar to PTCs there was large variability in the SFOAE tuning, with some curves more than twice as broad as the corresponding PTC. This was particularly the case for higher probe levels and higher residual criteria, see Figure 5 caption. For the remaining listeners for whom we obtained SFOAE STCs, the BW10 ratios ranged from 0.23 to 2.1, indicating that SFOAE STCs did not reliably reflect behavioral tuning. It should be remembered that we were able to obtain PTCs that had normal or nearly normal tuning for *all* of the 10–25 dB HL listeners (Figure 2, A; Figure 3, A). This observation reveals a major limitation in the use of SFOAE to measure frequency selectivity in cases of even subclinical hearing threshold elevation.

For the one listener in the 10–25 dB HL group (kc37), the SFOAE STCs obtained at 4 kHz were very irregular in shape (Figure 5, B), in contrast to “V” shaped PTCs with normal bandwidths (Figure 2, B, Figure 5, B, dashed black lines). Increasing the probe level from 10 to 20 dB SL resulted in downward shift of the SFOAE STCs (Charaziak et al, 2013). As the result the tips of 20-dB SL STCs were 15 to 25 dB below the tips of the corresponding PTCs, which contrasts with data obtained at 1 kHz (Figure 5, A) for a listener with similar hearing threshold and emission levels (kc42 in Table 1 vs. kc37 in Table 2). The interpretation of this discrepancy is uncertain.

The major problem with SFOAE STCs serving as an estimate of frequency selectivity in the 10–25 dB HL group was not only the large inter- and intra-subject variability as reported previously for normally-hearing listeners (Charaziak et al, 2013) but also that we were often

unable to measure SFOAE STCs at all, even in listeners with normal PTCs. The on-band SFOAE noise (e.g. Figure 4 grey dashed lines) seems to be the main reason for the poor SNR at higher probe levels in these listeners.

The 25–45 dB HL group—For the 1-kHz probe the 25–45 dB HL group tended to have the strongest SFOAEs at 10 dB SL (Table 1), suggesting that SFOAE STCs should be measurable for most of the criteria conditions considered. Yet, due to the high level of noise and/or inconsistency of the responses we could not obtain any SFOAE STCs at 10 dB SL. At higher probe levels only one listener (kc28), who also had broadened PTCs (Figure 2, A), demonstrated SFOAE residuals above the noise and we were able to obtain one SFOAE STC for 6/20 condition (Figure 5, C). The SFOAE STC was broader than the PTC (see caption for Figure 5), but it was also more than twice as broad as STCs collected in normally-hearing listeners (Charaziak et al, 2013). Thus, SFOAE STCs did reflect decreased behavioral frequency selectivity for this listener.

Difficulties in measuring SFOAE STCs for other conditions, such as for lower criteria or lower probe levels, for listener kc28 may serve as an example of the general issues we encountered in other cases. For example, attempts to decrease the residual criterion from 6 to 0 dB SPL for a 20 dB SL (59 dB SPL for kc28) probe also required lowering the noise rejection criterion to at least –6 dB SPL, which was generally close to the level of noise (Figure 4, C). As a result virtually all data points were rejected during the tracking procedure due to excessive noise. Attempts to decrease the probe level from 20 to 10 dB SL (49 dB SPL) resulted in a similar SNR problem (noise levels can be still relatively high, Figure 4, C). This limitation could not be compensated by increasing the residual criterion to 6 dB SPL because the residual was not large enough (Table 1). This example shows how challenging it can be to measure SFOAE STCs when higher probe levels must be used.

At the 4-kHz probe frequency we obtained a limited number of SFOAE STCs (only for listeners kc32 and kc38; total of four curves). As described above, the major problem was to adjust the residual criterion to be high enough so that the SNR is at least 6 dB, but still below the estimated total SFOAE level at a given SL. Most of the SFOAE STCs were obtained for listener kc32 (Figure 5, D). Interestingly, this listener's PTCs did not indicate abnormal tuning, while the SFOAE STCs were nearly twice as broad as SFOAE STCs recorded at equivalent conditions in normally-hearing listeners (Charaziak et al, 2013). For listener kc38 we were able to obtain a 6/10 SFOAE STC which was nearly identical to the SFOAE STC of kc32 measured with the same parameters. This is an interesting observation taking into account very different PTC results for these two listeners – suggesting nearly normal tuning for listener kc32 and abnormally broad tuning for kc38 (Figure 2, B, see the ID numbers). Thus, SFOAE STCs indicated that both of these listeners have similar frequency selectivity, yet their PTCs indicated that they did not.

Additional OAE measurements: SFOAE vs. DPOAE levels

The OAE generation models indicate that so called “single-source emissions” (e.g. SFOAE, SOAE) should be superior for characterizing cochlear function, compared to emissions having multiple sources of generation, such as DPOAE (Zweig & Shera, 1995; Shera &

Guinan, 1999). In support of this view, while SFOAEs and SOAEs are completely abolished following administration of aspirin, DPOAEs remain almost unchanged (Martin et al, 1988; Wier et al, 1988). Also SFOAEs outperform DPOAEs in identifying hearing loss at 0.5 kHz, but both tests have similar success rates at higher frequencies (Ellison & Keefe, 2005). Thus, SFOAE STCs may be a better alternative for estimating frequency selectivity than DPOAE STCs. While this claim seems to be valid for normally-hearing listeners (<10 dB HL), at least at the group level (Charaziak et al, 2013), attempts to measure SFOAE STCs in listeners with hearing thresholds <10 dB HL were challenging and often unsuccessful, usually due to poor SNR. Animal data on DPOAE STCs obtained following cochlear manipulations known to disrupt frequency selectivity have been inconclusive (e.g. Martin et al, 1998; Howard et al, 2003). However it has been shown that DPOAE STCs can indicate slightly broader tuning in humans with mild-to-moderate sensorineural hearing loss than for individuals with normal hearing (Abdala & Fitzgerald, 2003; Gorga et al, 2003; Gruhlke et al, 2012). Does this mean that DPOAE STCs may be a better choice for estimating frequency selectivity because they can be more reliably recorded than SFOAE STCs in cases of hearing loss? To obtain more insight into that problem we collected some additional data, namely SFOAE and DPOAE level vs. frequency functions at equivalent probe levels (60 dB SPL; see Supplementary OAE measurements). The data for three listeners with different degrees of hearing loss at 1 kHz (but similar HL at 4 kHz, see Figure 1 dashed lines with ID numbers for audiograms) are shown in Figure 6 (black solid lines, SFOAEs plotted in the left columns, DPOAEs in the right). Clearly, SFOAEs were much noisier than DPOAEs, particularly for higher probe frequencies (the noise levels are shown with grey dashed lines). This is another demonstration of the on-band noise present for SFOAEs at higher probe levels (Figure 4, see also Schairer & Keefe, 2005). As observed by others, on-band noise was not present for DPOAEs because, unlike the case of SFOAEs, there was no stimulus energy at the OAE frequency (e.g. Schairer & Keefe, 2005). The noise seen at lower stimulus levels (dashed grey) was not elevated even when the stimulus levels for DPOAE measurements were increased to 75 dB SPL (Figure 6, B, D, F, solid grey). Thus unlike the case of SFOAEs, increasing the levels of stimuli for DPOAEs improves SNR, which would plausibly permit measuring STCs. An interesting case was listener kc39, for whom DPOAEs tested at 75 dB SPL demonstrated levels that were still below the SFOAE noise (Figure 6, C, D), indicating a potential for high-level DPOAE STC measurements in listeners where measuring SFOAE STCs would not be possible.

Limitations and future directions

The on-band noise of SFOAE seems to be the major obstacle for obtaining SFOAE STCs at higher probe levels with the suppression method used in this study. However, an alternative method for measuring SFOAEs has been proposed that may minimize or eliminate the problem of the on-band noise (Neely et al, 2005). Briefly, in this method the SFOAE level is extracted from the energy present in sidebands of the SFOAE produced by using a suppressor that is amplitude modulated at a low frequency. The method is referred to as AM-SFOAE (amplitude modulated SFOAE). Hence, there is no stimulus energy at the frequencies of the side bands used to estimate SFOAE and thus, as observed for DPOAEs, there should be no on-band noise. Indeed, the noise levels of AM-SFOAE input-output functions fluctuated around -25 dB SPL across a 0–60 dB SPL range of probe level (Neely

et al, 2005; Johnson & Beshaler, 2013). It is possible that adapting the AM-SFOAE method for tuning measurements may produce better data at the higher probe levels that must be used in cases of abnormal hearing thresholds, compared with the suppression method used in this study.

Another factor that could have contributed to the difficulty of obtaining SFOAE STCs at higher probe levels is our choice of a tracking paradigm with a predefined noise rejection criterion for finding suppressor levels that require that the SFOAE residual criterion be within a narrow window (± 1 dB). Although the tracking paradigm is time-efficient it is also compromised by noisy data that prevent the tracking algorithm from converging to the criterion.

Lastly, It is important to note that the behavioral methods for estimating cochlear sharpness of tuning are not without their own limitations and there is no consensus for which behavioral paradigm is optimal (e.g. Oxenham and Shera, 2003; Ruggero & Temchin, 2005). Simultaneous-masked PTCs have been used widely to estimate frequency selectivity (e.g. Florentine et al, 1980; Stelmachowicz et al, 1985; Moore & Glasberg, 1986) and closely mimic the paradigm we used for SFOAE STC measurements. Thus, simultaneous-masked PTCs thus seemed to be an optimal choice for the purposes of this report, despite the possibility that they may not be the best approach for estimating cochlear frequency selectivity.

Conclusions

Despite their potential, SFOAE STCs do not accurately or reliably predict behavioral tuning in listeners with hearing impairment, primarily due to difficulties in obtaining satisfactory SNR at higher probe levels that prevented us from measurements of SFOAE STCs in many cases. In the cases where we were able to obtain SFOAE STCs we noted a large variability in agreement with behavioral tuning, as also observed for normally-hearing subjects (Charaziak et al, 2013). To some degree this variability may reflect the influence of on-band noise on SFOAE STC measurements. It is possible that SFOAE STC measured with an alternate method (e.g. AM-SFOAE) may be free of the on-band noise problem and serve as a more reliable estimate of cochlear processes when higher probe levels must be used.

Acknowledgements

This work was supported by NIDCD grant DC006014 (P. Souza) Northwestern University, and AAA Student Investigator Research Grant 2011 (K. Charaziak).

Abbreviations

BW10	Tuning curve bandwidth (in kHz) measured 10 dB above the tip
DPOAE	Distortion product otoacoustic emission
f_{probe}	Frequency of the probe tone
IO	Input-output function

OAE	Otoacoustic emission
PTC	Psychophysical tuning curve
SFOAE	Stimulus-frequency otoacoustic emission
SNR	Signal-to-noise ratio
STC	Suppression tuning curve
TEOAE	Transient-evoked otoacoustic emission

References

- Abdala C, Fitzgerald TS. Ipsilateral distortion product otoacoustic emission (2f1-f2) suppression in children with sensorineural hearing loss. *J Acoust Soc Am.* 2003; 114:919–931. [PubMed: 12942973]
- Baiduc RR, Lee J, Dhar S. Spontaneous otoacoustic emissions, threshold microstructure, and psychophysical tuning over a wide frequency range in humans. *J Acoust Soc Am.* 2014; 135:300–314. [PubMed: 24437770]
- Brass D, Kemp DT. Suppression of stimulus frequency otoacoustic emissions. *J Acoust Soc Am.* 1993; 93:920–939. [PubMed: 8445127]
- Charaziak KK, Souza P, Siegel JH. Time-efficient measures of auditory frequency selectivity. *Int J Audiol.* 2012; 51:317–325. [PubMed: 22107443]
- Charaziak KK, Souza P, Siegel JH. Stimulus-frequency otoacoustic emission suppression tuning in humans: Comparison to behavioral tuning. *J Assoc Res Otolaryngol.* 2013; 14:843–862. [PubMed: 24013802]
- Cheatham, MA.; Katz, ED.; Charaziak, KK.; Dallos, P.; Siegel, JH. Using stimulus frequency emissions to characterize cochlear function in mice. *AIP Conference Proceedings*; 2011. p. 383–388.
- Dorn PA, Piskorski P, Keefe DH, Neely ST, Gorga MP. On the existence of an age/threshold/frequency interaction in distortion product otoacoustic emissions. *J Acoust Soc Am.* 1998; 104:964–971. [PubMed: 9714916]
- Ellison JC, Keefe DH. Audiometric predictions using stimulus-frequency otoacoustic emissions and middle-ear measurements. *Ear Hear.* 2005; 26:487–503. [PubMed: 16230898]
- Florentine M, Buus S, Scharf B, Zwicker E. Frequency selectivity in normally-hearing and hearing-impaired observers. *J Speech Hear Res.* 1980; 23:646–669. [PubMed: 7421164]
- Gorga MP, Neely ST, Dierking DM, Dorn PA, Hoover BM, et al. Distortion product otoacoustic emission suppression tuning curves in normal-hearing and hearing-impaired human ears. *J Acoust Soc Am.* 2003; 114:263–278. [PubMed: 12880040]
- Gruhlke A, Birkholz C, Neely ST, Kopun J, Tan H, et al. Distortion-product otoacoustic emission suppression tuning curves in hearing-impaired humans. *J Acoust Soc Am.* 2012; 132:3292–3304. [PubMed: 23145613]
- Harris FP, Probst R, Xu L. Suppression of the 2f1-f2 otoacoustic emission in humans. *Hear Res.* 1992; 64:133–141. [PubMed: 1490896]
- Howard MA, Stagner BB, Foster PK, Lonsbury-Martin BL, Martin GK. Suppression tuning in noise-exposed rabbits. *J Acoust Soc Am.* 2003; 114:279–293. [PubMed: 12880041]
- Johnson TA, Beshaler L. Influence of stimulus parameters on amplitude-modulated stimulus frequency otoacoustic emissions. *J Acoust Soc Am.* 2013; 134:1121–1133. [PubMed: 23927112]
- Johnson, TA.; Gorga, MP.; Neely, ST.; Oxenham, AJ.; Shera, CA. Relationships between otoacoustic and psychophysical measures of cochlear function. In: Manley, GA.; Fay, RR.; Popper, AN., editors. *Active Processes and Otoacoustic Emissions in Hearing*. Springer; New York: 2007. p. 395–420.

- Johnson TA, Neely ST, Garner CA, Gorga MP. Influence of primary-level and primary-frequency ratios on human distortion product otoacoustic emissions. *J Acoust Soc Am*. 2006; 119:418–428. [PubMed: 16454296]
- Kalluri R, Shera CA. Comparing stimulus-frequency otoacoustic emissions measured by compression, suppression, and spectral smoothing. *J Acoust Soc Am*. 2007; 122:3562–3575. [PubMed: 18247764]
- Keefe DH, Ellison JC, Fitzpatrick DF, Gorga MP. Two-tone suppression of stimulus frequency otoacoustic emissions. *J Acoust Soc Am*. 2008; 123:1479–1494. [PubMed: 18345837]
- Kemp DT. Stimulated acoustic emissions from within the human auditory system. *J Acoust Soc Am*. 1978; 64:1386–1391. [PubMed: 744838]
- Kemp, DT. Otoacoustic emissions: The basics, the science and the future potential. In: Robinette, MS.; Glatke, TJ., editors. *Otoacoustic Emissions: Clinical Applications*. Theime; New York: 2007. p. 7-42.
- Kemp, DT.; Chum, RA. Observations on the generator mechanism of stimulus frequency acoustic emissions: Two tone suppression. In: Deboer, E.; Viergever, MA., editors. *Psychophysical, Physiological and Behavioral Studies in Hearing*. Delft University Press; Delft: 1980. p. 34-41.
- Kee J, Dhar S, Abel R, Banakis R, Grolley E, et al. Behavioral hearing thresholds between 0.125 and 20 kHz using depth-compensated ear simulator calibration. *Ear Hear*. 2012; 33:315–329. [PubMed: 22436407]
- Margolis RH, Heller JW. Screening tympanometry: Criteria for medical referral. *Audiology*. 1987; 26:197–208. [PubMed: 3632475]
- Martin GK, Jassir D, Stagner BB, Lonsbury-Martin BL. Effects of loop diuretics on the suppression tuning of distortion-product otoacoustic emissions in rabbits. *J Acoust Soc Am*. 1998; 104:972–983. [PubMed: 9714917]
- Martin GK, Lonsbury-Martin BL, Probst R, Coats AC. Spontaneous otoacoustic emissions in a nonhuman primate. 1. Basic features and relations to other emissions. *Hear Res*. 1988; 33:49–68. [PubMed: 3372370]
- Moore BC, Glasberg BR. Comparisons of frequency selectivity in simultaneous and forward masking for subjects with unilateral cochlear impairments. *J Acoust Soc Am*. 1986; 80:93–107. [PubMed: 3745670]
- Moore, BCJ. *Cochlear Hearing Loss*. John Wiley & Sons, Ltd; 2008. Masking, frequency selectivity and basilar membrane nonlinearity; p. 45-91.
- Moore BCJ, Vickers DA, Plack CJ, Oxenham AJ. Inter-relationship between different psychoacoustic measures assumed to be related to the cochlear active mechanism. *J Acoust Soc Am*. 1999; 106:2761–2778. [PubMed: 10573892]
- Neely ST, Johnson TA, Garner CA, Gorga MP. Stimulus-frequency otoacoustic emissions measured with amplitude-modulated suppressor tones. *J Acoust Soc Am*. 2005; 118:2124–2127. [PubMed: 16266132]
- Oxenham AJ, Shera CA. Estimates of human cochlear tuning at low levels using forward and simultaneous masking. *J Assoc Res Otolaryngol*. 2003; 4:541–554. [PubMed: 14716510]
- Robinson JD, Baer T, Moore BC. Using transposition to improve consonant discrimination and detection for listeners with severe high-frequency hearing loss. *Int J Audiol*. 2007; 46:293–308. [PubMed: 17530514]
- Robles L, Ruggero MA. Mechanics of the mammalian cochlea. *Physiol Rev*. 2001; 81:1305–1352. [PubMed: 11427697]
- Ruggero MA, Temchin AN. Unexceptional sharpness of frequency tuning in the human cochlea. *Proc Natl Acad Sci USA*. 2005; 102:18614–18619. [PubMed: 16344475]
- Schairer KS, Fitzpatrick D, Keefe DH. Input-output functions for stimulus-frequency otoacoustic emissions in normal-hearing adult ears. *J Acoust Soc Am*. 2003; 114:944–966. [PubMed: 12942975]
- Schairer KS, Keefe DH. Simultaneous recording of stimulus-frequency and distortion-product otoacoustic emission input-output functions in human ears. *J Acoust Soc Am*. 2005; 117:818–832. [PubMed: 15759702]

- S k A, Alcantara J, Moore BCJ, Kluk K, Wicher A. Development of a fast method for determining psychophysical tuning curves. *Int J Audiol*. 2005; 44:408–420. [PubMed: 16136791]
- Shera CA, Guinan JJ Jr. Evoked otoacoustic emissions arise by two fundamentally different mechanisms: A taxonomy for mammalian OAEs. *J Acoust Soc Am*. 1999; 105:782–798. [PubMed: 9972564]
- Stelmachowicz PG, Jesteadt W. Psychophysical tuning curves in normal-hearing listeners: Test reliability and probe level effects. *J Speech Hear Res*. 1984; 27:396–402. [PubMed: 6482409]
- Stelmachowicz PG, Jesteadt W, Gorga MP, Mott J. Speech perception ability and psychophysical tuning curves in hearing-impaired listeners. *J Acoust Soc Am*. 1985; 77:620–627. [PubMed: 3973233]
- Wier CC, Pasanen EG, Mcfadden D. Partial dissociation of spontaneous otoacoustic emissions and distortion products during aspirin use in humans. *J Acoust Soc Am*. 1988; 84:230–237. [PubMed: 3411052]
- Zurek PM. Spontaneous narrowband acoustic signals emitted by human ears. *J Acoust Soc Am*. 1981; 69:514–523. [PubMed: 7462474]
- Zweig G, Shera CA. The origin of periodicity in the spectrum of evoked otoacoustic emissions. *J Acoust Soc Am*. 1995; 98:2018–2047. [PubMed: 7593924]
- Zwicker, E. On a psychoacoustical equivalent of tuning curves. In: Zwicker, E.; Terhardt, E., editors. *Facts and Models in Hearing*. Springer-Verlag; Berlin: 1974. p. 132-140.
- Zwicker E, Schorn K. Psychoacoustical tuning curves in audiology. *Audiology*. 1978; 17:120–140. [PubMed: 646730]
- Zwicker E, Wesel J. The effect of addition in suppression of delayed evoked otoacoustic emissions and in masking. *Acta Acustica*. 1990; 70:189–196.

Figure 1.

Hearing thresholds normalized to mean hearing thresholds of normal-hearing young adults, so that the 0 line corresponds to thresholds of 22–35 year old adults (from Lee et al, 2012). Based on the relative hearing threshold level at 1 kHz or 4 kHz, each subject was qualified to one of three experimental groups: <10 dB HL (light grey box), 10–25 dB HL (medium grey box), or 25–45 dB HL (dark grey box). The number of listeners assigned to each group at 1 kHz and 4 kHz is shown in the appropriate shade of grey within the figure. The audiograms of three listeners (kc32, 36, and 39) for whom additional OAE data are displayed in Figure 6 are emphasized with dashed lines and symbols with the listeners' IDs.

Figure 2.

The widths of PTCs (bandwidth 10 dB above the tip in kHz, BW10) as a function of probe level (dB SPL) at 1 kHz (A) and 4 kHz (B). Each data point (marked as listener's ID number) represents the mean width (BW10) for upward- and downward-sweep PTCs for each listener (note: at 4 kHz BW10 could be calculated only for the upward-sweep PTC for kc28 and only for the downward-sweep PTC for kc39). For listener kc27 at the 1 kHz probe frequency and for kc36 at 4 kHz the PTCs were too "flat" to calculate BW10s (Figure 3, C, D). For comparison, the BW10s for PTCs collected in listeners with normal hearing are shown with black triangles (Charaziak et al, 2013). All PTCs were measured at 10 dB SL with the exception of two listeners who were also tested at 20 dB SL and 30 dB SL (dotted lines). The HL group assignments are shown with grey-shaded boxes.

Figure 3.

Individual LOESS-smoothed PTCs (upward masker sweep) at 1 kHz (A and C) and 4 kHz (B and D). Data for the 10–25 dB HL group are shown in panels A and B, and for the 25–45 dB HL group are shown in panels C and D. The saturation of the grey shading corresponds to the degree of hearing loss within a given HL group, with darker shading indicating higher thresholds (see Table 1, Table 2, and listeners' ID number listed near each curve). For comparison an average PTC for normal-hearing listeners is shown in each panel (black dashed line; Charaziak et al, 2013).

Figure 4. Median SFOAE input-output functions (solid black) and median noise levels (dashed grey) for probe frequencies 1 kHz (A–C) and 4 kHz (D) across different HL groups. The error bars represent 25th and 75th percentiles.

Figure 5.

Examples of SFOAE STCs obtained for the 10–25 dB HL listeners (A, B) and the 25–45 dB HL listeners (C, D) at 1 kHz (A, C) and at 4 kHz (B, D). The more saturated the grey line the higher the SFOAE criterion that was used while the line type (dotted, solid, and dashed-dotted) codes the probe level (see the legend; residual criterion in dB SPL/probe level in dB SL). The PTCs for upward- and downward-sweeps are shown in black dashed lines. For listener kc42 the BW10 ratios ranged from 0.9 to 2.2. For listener kc37 (B) meaningful BW10 could be calculated only for 0/20 SFOAE STCs, resulting in a BW10 ratio of 0.65. For listener kc28 the BW10 ratio was equal to 1.6. For listener kc32 (D) the BW10 ratios were 1.5 and 1.6 (excluding 6/20 STC for which it was not possible to calculate BW10).

Figure 6. SFOAE (A, C, E) and DPOAE (B, D, F) levels as a function of the probe frequency (f_2 for DPOAEs) for three listeners (rows).

Table 1

Optimized probe frequencies (near 1 kHz) from each individual's SFOAE fine structure and corresponding hearing thresholds. The SFOAE residual level at 10, 20, and 30 dB SL was estimated based on their SFOAE IO function (note: it was not possible to estimate the SFOAE residual level in some listeners due to poor SNR or when probe level in dB SL exceeded highest SPL tested). Within each group the listeners were listed in order of the smallest degree of hearing loss to the largest degree.

Group	Listener ID/ gender/ear	Hearing threshold (dB SPL)	f_{probe} (kHz)	SFOAE level (dB SPL) at:		
				10 dB SL	20 dB SL	30 dB SL
< 10 (dB HL)	kc38FR	11	0.904	-3.2	4.2	12.7
	kc31FL	16	1.055	-4.5	2.8	7.9
	kc36ML	19	0.904	6.9	12.7	19.1
	Average (SD)	15.3 (4.0)	–	-0.28 (6.27)	6.6 (5.4)	13.2 (5.6)
10–25 (dB HL)	kc42MR	23	1.012	-0.5	5.9	18.2
	kc41ML	27	1.012	-6.6	2.8	8.0
	kc30FL	28	1.033	-4.0	5.5	8.8
	kc37ML	30	0.925	4.0	7.3	12.3
	kc33FR	31	1.077	-8.3	1.2	10.4
	kc35FL	32	1.033	-1.5	4.2	10.5
	kc39MR	33	0.968	-10.3	2.4	n.a.
	Average (SD)	29.1 (3.4)	–	-3.9 (5.0)	4.2 (2.2)	11.1 (4.3)
25–45 (dB HL)	kc28FL	39	1.055	1.4	10.8	14.2
	kc32MR	50	1.098	14.3	n.a.	n.a.
	kc27MR	51	0.904	1.6	n.a.	n.a.
	Average (SD)	46.7 (6.7)	–	5.8 (7.4)	n.a.	n.a.

Table 2

Optimized probe frequencies (near 4 kHz) from each individual's SFOAE fine structure and corresponding hearing thresholds. Please see the caption for Table 1 for more details. Note: four listeners had hearing thresholds exceeding 45 dB HL at 4 kHz (see Figure 1), and the SFOAE levels did not meet the dual requirements of level of at least –6 dB SPL plus SNR of at least 6 dB (see SFOAE measurements). Listener kc41ML did not have SFOAEs meeting the requirements, despite having hearing thresholds <45 dB HL.

Group	Listener ID/ gender/ear	Hearing threshold (dB SPL)	f_{probe} (kHz)	SFOAE level (dB SPL) at:		
				10 dB SL	20 dB SL	30 dB SL
10–25 (dB HL)	kc37ML	35	3.897	–5.2	6.7	n.a.
25–45 (dB HL)	kc42MR	47	4.112	–2.6	10.5	n.a.
	kc31FL	49	3.854	–0.4	3.0	n.a.
	kc32MR	49	3.897	7.7	7.1	n.a.
	kc36ML	55	4.026	–1.6	n.a.	n.a.
	kc28FL	55	4.005	–1.8	n.a.	n.a.
	kc41ML	55	4.112	n.a.	n.a.	n.a.
	kc38FR	57	4.155	11.2	n.a.	n.a.
	kc39MR	58	4.026	16.0	n.a.	n.a.
Average (SD)		54 (3.6)	–	4.1 (7.5)	6.9 (3.7)	–