Towards a joint reflection-distortion otoacoustic emission profile: Results in normal and impaired ears

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Otoacoustic emissions (OAEs) provide salient information about cochlear function and dysfunction. Two broad classes of emissions, linear reflection and nonlinear distortion, arise via distinct cochlear processes and hence, appear to provide independent information about cochlear health and hearing. Considered in combination, these two OAE types may characterize sensory hearing loss most effectively. In this study, the level-dependent growth of stimulus-frequency OAEs (a reflection-type emission) and distortion-product OAEs (a distortion-type emission) were measured in ten normal-hearing ears and eight ears with slight-to-moderate sensorineural hearing loss. Metrics of OAE strength and compression were derived from OAE input/output functions and then considered in a combined fashion. Results indicate that SFOAEs and DPOAEs differ significantly in their strength and compression features. When SFOAE and DPOAE metrics are displayed together on a two-dimensional plot, relatively well-defined data clusters describe their normative relationship. In hearing-impaired ears, this relationship is disrupted but not in a uniform way across ears; ears with similar audiograms showed differently altered joint-OAE profiles. Hearing loss sometimes affected only one OAE or one more than the other. Results suggest a joint-OAE profile is promising and warrants study in a large group of subjects with sensory hearing loss of varied etiologies. © 2017 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4996859>]

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I. INTRODUCTION

There are two broad classes of otoacoustic emissions, one created by nonlinear distortion and another by linear, back-scattered reflections. These two classes of emissions appear to be sensitive to distinct cochlear properties (Shera and Guinan, 1999). Initially, all otoacoustic emissions (OAEs) were thought to be generated by distortion associated with outer hair cell (OHC) electromotility (Kemp, 1978). As such, OAEs were—and generally continue to be—used interchangeably for the assessment of hearing in clinics and often in laboratories. During the last decade and a half, this unitary view of OAEs has been revised. Nonlinearity is only one of two basic mechanisms by which backward traveling energy is initiated within the cochlea. The second mechanism is linear reflection. *Reflection emissions* are thought to arise from micromechanical irregularities along the cochlea, which produce a backscattering of wavelets near the peak of the traveling wave (Zweig and Shera, 1995; Shera and Guinan, 1999). A coherent summation of the reflected wavelets emerges into the ear canal as a reflection emission. The simplest reflection emission is the stimulus-frequency OAE (SFOAE) generated by a single low-level pure tone. *Distortion emissions*, exemplified by the distortion-product otoacoustic emission (DPOAE), originate in the nonlinear force-generating process of the outer hair cell (e.g., Hudspeth and Corey, 1977). The DPOAE is made up of two components, a dominant nonlinear-distortion

component generated near the overlap of the eliciting tones, and a smaller reflection component which arises from the backscattering of the distortion wave near the $2f_1$ - f_2 site (Shera and Guinan, 1999; Talmadge *et al.*, 1999; Knight and Kemp, 2001). In this study, we measure only the isolated distortion component of the DPOAE as an indicator of cochlear nonlinearity and remove the reflection components. For brevity and clarity, we have presented a simplified taxonomy for reflection and distortion emission generation (and interested readers are referred to Shera and Guinan, 1999, for more detail); however, both OAEs are subject to common dependencies on OHC integrity and cochlear amplification.

Current OAE generation models suggest that while distortion emissions are best suited to probe the strength and form of cochlear nonlinearities underlying their generation, reflection emissions, dominated by back-scattering from the peak of the traveling wave, best probe features such as near-threshold tuning and cochlear amplifier gain, which are also strongest at the peak (Robles and Ruggero, 2001; Shera and Guinan, 1999). *The potential value of this mechanistic framework is that each of the two classes of emission gauge distinct cochlear properties.* Strong experimental evidence supports the idea that reflection and distortion emissions can change independently as reviewed in the following section.

A. Independent changes in reflection and distortion OAEs

In humans, reflection emissions are reduced more by salicylates (Long and Tubis, 1988; Wier *et al.*, 1988; Stewart and Hudspeth, 2000; Rao and Long, 2011) and medial

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fferent activation (Abdala *et al.*, 2009; Deeter *et al.*, 2009; Henin *et al.*, 2011) than are distortion emissions. Dissociation of the two emission types is also evident during maturation, the reflection-component of the DPOAE contributing more to the ear-canal emission in newborns than in adults (Abdala and Dhar, 2010, 2012; Kalluri and Abdala, 2015). As an individual ages, the distortion-component of the DPOAE is reduced more than is reflection, which also produces an increase in DPOAE fine structure with age (Abdala and Dhar, 2012). Click-evoked OAEs (CEOAEs) are a reflection-type emission (Kalluri and Shera, 2007b) and are more affected by mild levels of hearing loss than are DPOAEs (Gorga *et al.*, 1993; Gorga *et al.*, 1997; Lapsley-Miller *et al.*, 2004). Basic patterns of response growth (i.e., input/output characteristics) differ between the two OAE types as well; DPOAEs saturate at moderate primary-tone levels whereas SFOAEs show incipient compression at lower stimulus levels (Abdala, 2000; Dorn *et al.*, 2001; Schairer and Keefe, 2005; Kalluri and Shera 2007b; Ortmann and Abdala, 2016).

Laboratory animals can elucidate differences between distortion and reflection OAE types. Reflection emissions are more robust than distortion emissions in primates whereas in rodents, the opposite is true (Zurek, 1985; Whitehead *et al.*, 1996). Perhaps the most compelling evidence for their non-redundance and independent sensitivities comes from transgenic mice. Several transgenic mouse strains with pointed cochlear anomalies alter reflection and distortion OAEs independently. For example, the Ceacam16 mouse, which has a deficient and porous tectorial membrane, has shown normal-magnitude DPOAEs but abnormally large and numerous reflection OAEs, including both spontaneous and stimulus-frequency OAEs (Cheatham *et al.*, 2014). The stereocilin-deficient mouse has abnormal lateral links among hair cell stereocilia, and lacks DPOAEs though it shows near-normal sensitivity and tuning early in life, which would suggest present reflection emissions had they been measured (Verpy *et al.*, 2008).

Collectively, this body of evidence in humans and non-humans indicates that distortion and reflection emissions are sensitive to distinct cochlear properties and can be impacted independently by various manipulations. These observations raise an unanswered question: *Can we probe the form and origin of cochlear dysfunction by measuring both distortion and reflection OAEs and considering their combined outcomes?*

Prior to addressing this question, we must establish that reflection emissions, and most notably SFOAEs, can be reliably recorded in human ears with sensorineural hearing loss (SNHL). We know that DPOAEs can be recorded in impaired ears (e.g., Martin *et al.*, 1990) but there is a pervasive and mistaken notion that reflection OAEs cannot be recorded in ears with hearing loss. Evidence exists to counter this notion from among the earliest published OAE reports. Click-evoked OAEs have been recorded in impaired ears (Kemp, 1978; Kemp *et al.*, 1986; Bonfils *et al.*, 1988; Collet *et al.*, 1993; Probst and Harris, 1993) and are routinely recorded in audiology clinics for the assessment of hearing loss. SFOAEs have not been so amply characterized in ears with SNHL but even here, a handful of studies have been published measuring SFOAEs in impaired human ears

(Konrad-Martin *et al.*, 2002; Ellison and Keefe, 2005; Charaziak *et al.*, 2014; Abdala and Kalluri, 2015). The misperception about our inability to record SFOAEs in ears with SNHL is likely due to early impressions that SFOAEs were too technically difficult to measure; SFOAEs can require extensive averaging to coax signals out of the noise, and systems to measure SFOAEs are not yet available in commercial instrumentation.

B. Utilizing OAEs fully

In audiology clinics and hospital nurseries throughout the country, OAEs are mostly applied in a rudimentary thumbs-up/thumbs-down manner, to screen for and detect hearing loss. *However, by limiting the goal to screening and detection, OAEs may be grossly under-utilized.* Applying these two classes of OAEs—reflection and distortion—interchangeably or in isolation neglects their distinct contributions and may dilute information about the cochlear dysfunction and the origin of the deficit producing mild-to-moderate SNHL. In this study, we exploit the combined information offered by reflection and distortion OAEs and define the normative profile of distortion-to-reflection OAE energy in healthy young-adult ears. We then generate the same profile in a small group of mildly hearing-impaired individuals, measuring reflection and distortion OAEs in the same ear over a broad parametric space and considering their combined outcome. This is a novel approach to OAE measurement. It focuses on assessing the integrity of distinct cochlear processes embodied by each OAE so as to distinguish among distinct cochlear deficits, in particular those manifesting a similar outward audiogram. We hypothesize, given their distinct sources, that a dual reflection-distortion OAE profile may be more informative in understanding cochlear function and dysfunction than either emission measured alone.

II. METHODS

A. Subjects

A total of 18 individuals served as subjects in this study: ten normal-hearing adult subjects and eight adults with slight-to-moderate sensorineural hearing loss (SNHL). The ten normal hearers [audiometric thresholds <15 dB hearing level (HL) from 0.5 to 8 kHz] ranged from 17 to 53 years of age with a mean age of 26 years (8 females; 2 males; 10R ears). The hearing-impaired group ranged from 25 to 74 years with a mean age of 47 years (4 females; 4 males; 6R; 2L ears). Figure 1 provides the eight audiograms corresponding to the test ear of each hearing-impaired subject.

B. Instrumentation and signal processing

1. SFOAE

Stimulus generation and SFOAE acquisition were controlled using a MATLAB-based swept-tone algorithm (adapted from Kalluri and Shera, 2013) via a Babyface USB 2.0 High Speed Audio Interface (RME Audio, Germany) and an Etymotic Research ER-10C probe system. The stimuli were

FIG. 1. Audiograms for eight hearing-impaired subjects.

swept tones whose instantaneous frequency changed smoothly and linearly with time (in a downward direction) between 0.5 and 8 kHz at a rate of 2 kHz/s. A novel method of sweep presentation was applied for efficiency: four sweep segments, each spanning 1.8 kHz, were presented concurrently as a stack. Recent work has shown that as long as there is at least a one-octave separation between stacked frequency segments, the impact on SFOAE amplitude and phase is negligible (Abdala *et al.*, 2017); the advantage is that data collection time is cut to one-quarter the time required for a single sweep.

Stimulus-frequency OAEs were measured using an interleaved suppression paradigm (Shera and Guinan, 1999). SFOAE probe tones were presented from 10 to 60 dB sound pressure level (SPL) in 5–10 dB steps. Suppressor tones at 55–65 dB SPL were swept simultaneously, 50 Hz below the probe frequency. In-the-ear calibration of level (in dB SPL) was conducted at the initiation of each 64-sweep block throughout the test session. To record SFOAEs in normal hearers, between 64 and 256 sweeps were presented and averaged, with more sweeps presented at the lower probe levels; for hearing-impaired subjects, between 64 and 512 sweeps were presented. During a test session, blocks of 64 sweeps were added to data collection as needed to achieve adequate signal-to-noise (SNR).

2. DPOAE

Signal generation and recording were controlled using custom software on an Apple Macintosh laptop via a MOTU 828 Mk II input/output device (24 bits/44 100 Hz). Stimuli were presented to the ear via ER2 transducers. The output of the ER10B+ microphone was pre-amplified and then passed through an analog high-pass filter with 300-Hz cutoff frequency before being digitized by the MOTU and stored on disk. Distortion-product OAEs at $2f_1-f_2$ were measured with pairs of primary tones logarithmically swept upwards from

0.5 to 8 kHz at a rate of 0.5 octaves/s and a fixed f_2/f_1 of 1.22. Primary tones (L_2) were swept from 30 to 80 dB SPL in 5–10 dB step size using the “scissors” strategy to determine primary-tone level separation ($L_1 = 0.4 \times L_2 + 39$; Kummer *et al.*, 1998). We applied phase-rotation averaging to cancel the primary tones during DPOAE measurement (Whitehead *et al.*, 1996). Three stimulus intervals with different starting phases were interleaved such that f_1 and f_2 were cancelled when the block was averaged and only the DPOAE remained. For normal-hearing subjects between 16 and 24 sweeps were presented; for hearing impaired subjects, between 16 and 96 sweeps were presented. Sweeps were presented in blocks of 16, and additional blocks were added as needed to achieve adequate SNR.

Calibrated stimuli were delivered to each subject after compensating for the depth of probe insertion (Lee *et al.*, 2012). The half-wave resonance was initially recorded in the ear of each subject and associated with a probe insertion depth. The pressure response recorded for a matched insertion depth, which had been determined *a priori* in an ear simulator (IEC 60318-4; BK 4157), was then used to compensate the frequency response of the sound sources and to approximate a relatively flat response across frequency at the tympanic membrane. As a measure of probe stability, we monitored the half-wave resonance in the ear canal every 12 min throughout the test session.

C. Otoacoustic emissions

SFOAEs and DPOAEs were analyzed with a least squares fitting (LSF) technique (Long *et al.*, 2008; Kalluri and Shera, 2013; Abdala *et al.*, 2015). To apply LSF modeling, the time waveform recorded at the microphone was segmented into chunks or analysis windows, and models for the stimulus tones and the OAE were created. Signals of interest within specified analysis windows were then determined by a least squares fit, which minimizes the sum of the squared

residuals between the model and the data. The LSF analysis can be thought of as a moving bandpass filter with varying center frequencies corresponding to the frequency of the OAE (Long *et al.*, 2008). OAEs evoked with swept-tones and analyzed with an LSF technique produce estimates of amplitude and phase that are comparable to those generated with discrete tones (Long *et al.*, 2008; Kalluri and Shera, 2013; Abdala *et al.*, 2015). For measurement of the total DPOAE (including both distortion and reflection parts), the optimal LSF analysis-window duration is 125 ms when combined with a sweep rate of 0.5 octaves/s (Abdala *et al.*, 2015). However, to isolate the nonlinear distortion part of the DPOAE, a longer window must be applied (500 ms) with a relatively fast sweep (such as the rate used here) to effectively eliminate the longer-latency reflection energy, leaving the nonlinear distortion component (Long *et al.*, 2008; Abdala *et al.*, 2015). Only the distortion component of the total DPOAE was used in the joint OAE profile. Whenever the acronym DPOAE was used in the Results section or in figures, it refers only to isolated distortion part of the total DPOAE. For analysis of the SFOAE, LSF analysis windows were set at 100 ms with 2 kHz/s sweep rate. For both emission types, the noise floor was estimated by taking the difference between adjacent sweep pairs and applying the LSF to this difference.

D. Joint reflection-distortion OAE profile

There are various ways to create a joint-OAE profile, which provides combined information about both reflection and distortion emissions in an integrated fashion. Here, we use one such method in 18 adult ears. To create the joint OAE profile, we recorded the level-dependent growth of the separated distortion-component of the DPOAE and of the SFOAE, and derived metrics characterizing this growth. We chose to use the SFOAE as an index of cochlear reflection rather than the reflection-component of the total DPOAE for several reasons. First, separating the total DPOAE into components is imperfect with any of the existing methods (Abdala *et al.*, 2016) therefore, the extracted reflection component is always compromised. The SFOAE, in contrast, represents the most simple example of reflection as it is evoked by only one low-level tone whose parameters can be controlled. Second, the component separation process most often yields a low-level measure of reflection with less-than-ideal SNR, and third, it is not possible to quantify the strength (or effective “stimulus level”) of the distortion wave peaking at the $2f_1-f_2$ place and producing reflection. Finally, the separated reflection component is created by and driven by the intermodulation distortion that produced it, making it a less independent form of cochlear reflection than the SFOAE.

Although we derived these metrics for reflection and distortion emissions separately, we distilled the results of both SFOAE and DPOAE outcomes into joint indices to define and elucidate the *relationship* between the two emissions while exploiting the distinct information each offers. Both OAE types were measured in each test ear, typically during the same test session though in some subjects,

repeated visits were required. In these cases, the probe fit was adjusted until the half-wave resonance peak measured in the ear canal matched that of the first testing session.

The selected analysis frequencies (at which OAE I/O functions were created) were chosen for each ear based on individual spectra. This is one of the advantageous features of this OAE approach: *a priori* test frequencies are not selected and applied for all ears. Instead, depending on the pattern of individual fine structure, frequencies near stable segments of the spectrum such as peaks can be selected while frequencies near minima (which are sensitive to slight probe shifts), can be avoided. For SFOAEs, test frequencies included 100-Hz-wide frequency bands centered around peaks or plateaus in SFOAE spectra from 0.5 to 8 kHz. For DPOAEs, discrete test frequencies were selected to be within 50 Hz of the SFOAE test frequency. Four to six analysis frequencies were selected for normal-hearing subjects to characterize normative combined reflection and distortion OAEs in healthy ears across a broad frequency range. As this is an initial study (and part of a larger-scale effort), we analyzed only one frequency band in hearing-impaired ears: 1–2.5 kHz.

The vertical dashed line at 1.1 kHz in Figs. 2(A) and 2(D) depicts one analysis frequency in a normal-hearing ear. In this figure, reflection (SFOAE) and distortion (DPOAE) spectra are shown at each of the stimulus levels. Figures 2(B) and 2(E) illustrate an input/output function (OAE level versus probe level for the SFOAE and versus L_2 for the DPOAE) constructed at 1.1 kHz. To more easily visualize differences between the two emissions, we chose to normalize OAE magnitude by probe level or L_2 , dividing each estimate of OAE magnitude by stimulus level as shown in Figs. 2(C) and 2(F). This created what we termed OAE “gain functions” (termed “transfer functions” in Kalluri and Shera, 2007a). The gain function plots OAE level in dB re: stimulus level (in dB SPL); we consider this metric a measure of emission strength.

The OAE gain functions can be fit by an equation of the form $G = G_o / (1 + A/A_{CT})^\alpha$ where G_o is the peak strength (PS) of the emission, A is its amplitude, A_{CT} is the stimulus level at which response compression begins, and α is the slope of response compression about this level. These fits are shown in Figs. 2(C) and 2(F) as black (SFOAE) and gray (DPOAE) lines superimposed on the OAE data. As is evident, the fit generally characterized the growth of OAE strength across stimulus level well. The following three OAE metrics were derived from each fit: (1) *PS* ($G_o = 20\log_{10}G_o$) is the maximum OAE gain or strength, i.e., OAE level re: stimulus level. It is represented by the flat portion of the gain function (associated with the lowest stimulus levels), which is where the emission level is growing most vigorously; that is, the processes generating the emission are most effective. Unlike conventional metrics, it does register the highest OAE magnitude produced, which is likely to reside within the compressed region of the response and be less sensitive to the OAE generation mechanism; (2) *Compression Threshold* (CT; $A_{CT} = 20\log_{10}(A_{CT}/20\mu\text{Pa})$) is the stimulus level at which emission strength begins to decrease and the OAE begins to grow compressively; and (3) *Compression Slope* (CS; α)

FIG. 2. (Color online) (A) and (D) OAE spectra for stimulus-frequency (reflection) OAEs and the distortion-component of the DPOAE (distortion OAEs) respectively, in the same ear. Both spectra depict OAE magnitude at successively lower stimulus levels. In general, the systematically decreasing response magnitude indicates reduced stimulus levels (level is designated by color online). The noise floor is shown in light-gray. A vertical dashed line and arrow indicate one exemplar analysis frequency at 1.1 kHz. Input/output functions were created at all analysis frequencies. (B) and (E) The input-output function, which plots OAE magnitude as a function of stimulus level, at 1.1 kHz for both SFOAE and DPOAE data. (C) and (F) The input/output function at 1.1 kHz transformed into a “gain function” by dividing OAE magnitude at each level by stimulus level. The gain function plots the OAE in dB re: stimulus level, and is a measure of OAE strength. A fit was applied to gain functions as shown by the black (SFOAE) and dark gray (DPOAE) lines superimposed on the data to estimate three parameters: PS, CT, and CS.

characterizes the rate of compression in the OAE magnitude at stimulus levels beyond the CT.

Additionally, we included a fourth metric generated from the OAE input/output function: OAE level (dB SPL) measured at the CT identified by the fit. We termed this OAE $L@CT$. Unlike more conventional response-level comparisons, which might be conducted at uniform, fixed stimulus levels, here the comparison is equated or normalized by each OAE’s (and ear’s) own compression pattern; hence, the stimulus level at which this metric was taken necessarily varied among ears and between OAE types.

E. Analysis

To display normative results, we (1) plotted each of the three gain-function metrics across frequency with linear

regressions fit to the data and (2) displayed the two most informative metrics PS and CT on a two-dimensional x - y plot in one frequency-band to elucidate the normative relationship between the reflection (x) and distortion (y) OAEs in each ear and to visualize how OAEs in impaired ears compare to this normative relationship. One-way analyses of variance (ANOVAs) were conducted to test the differences between SFOAE versus DPOAE PS, CT, CS, and $L@CT$ metrics in normal hearers.

III. RESULTS

A. Normal-hearing

To familiarize the reader with the joint-profile metrics, Figs. 3(A) and 3(B) show a typical OAE gain function for

FIG. 3. (Color online) (A) and (B) The same SFOAE and DPOAE gain function presented in Fig. 2 at one analysis frequency and the three parameters derived from this fit: PS, CT, and CS. The smaller inset above the main panels provides a visual depiction of the SF and DP OAE fits superimposed: the SFOAE fit is typically higher than the DPOAE fit, indicating greater PS; and the compression “knee” in the fit typically occurs at higher stimulus levels for the DPOAE than SFOAE.

SFOAEs and DPOAEs in the same ear. This exemplar (at only one analysis frequency) illustrates the typical reflection-distortion OAE relationship and how the three parameters are derived in normal-hearing ears. PS in this normal ear is 10.7 dB higher for the SFOAE than the DPOAE while the CT occurs at stimulus levels that are 6 dB higher for the DPOAE than the SFOAE. The CS is not grossly different between the two OAEs; both responses show highly compressive growth at higher stimulus levels. The smaller inset in Fig. 3 is a normal template with SFOAE and DPOAE fits superimposed to help the reader visualize the typical reflection-to-distortion relationship. In all normal-hearing ears, the flattened portion of the black fit (i.e., the PS) is at higher levels than the comparable flat segment of the gray fit, which tells us that the SFOAE is stronger at this test frequency. However, the bend in the fit (CT) occurs at higher stimulus levels for the gray fit compared to the black, which tells us that the DPOAE shows response compression at higher stimulus levels than the SFOAE. These are fundamental differences between the level-dependent growth and strength of reflection and distortion emissions.

Although Fig. 3 provides a typical template of the relationship between reflection and distortion emissions in the healthy ear, it provides data at only one frequency. In normal-hearers we defined the distribution of PS, CT, and CS across frequency for each ear. Figure 4 shows these metrics for both OAEs across frequency in ten normal-hearing ears. Linear regressions are fit to the data of SFOAEs and DPOAEs separately to help visualize the trends. Data in Fig. 4(A) for PS suggests the characteristic pattern of significantly stronger reflection than distortion OAEs across frequency. An ANOVA testing the SFOAE-DPOAE difference in PS was significant ($f = 57.4$; $p < 0.0001$). The CT [Fig. 4(B)] data show a slight frequency dependence for both OAEs but more notably, DPOAE magnitude compresses at significantly higher stimulus levels than SFOAE magnitude, as shown by an ANOVA ($f = 24.7$; $p < 0.0001$). Both responses are equally compressed once the compression “knee” is reached, as Displayed in Fig. 4(C). No significant difference was found between CS values derived from SFOAEs versus DPOAEs. However, it is clear that CS was less variable across frequency and subjects for DPOAE data. SFOAE estimates of the CS may be less reliable because the SFOAE probe was not presented at high enough probe levels to allow for an optimal estimate of this parameter.

An effective route by which to elucidate the relationship between distortion and reflection OAEs is on a two-dimensional x - y plot for one metric and test frequency at a time. Figure 5(A) depicts the normal distribution of PS for both SFOAE and DPOAEs at a frequency band of 1–2.5 kHz (this is the same frequency-band available in hearing-impaired subjects for later comparison). The 75% interquartile range is shown by horizontal and vertical bars. This joint index is a potentially powerful way to merge the properties of each OAE onto one informative metric, with the position of the data points in two-dimensional space depicting the relationship between the two OAEs. In fact, we see that joint OAE PS is defined by a cluster below the diagonal. Most ears fall just at or below the diagonal, elucidating a trend

FIG. 4. Three metrics derived from SFOAE (open circles) and DPOAE (gray squares) gain functions are shown in normal-hearing ears. PS, CT, and CS are plotted as a function of analysis frequency. Linear regressions are plotted on the data for each OAE-type separately. PS was greater for SFOAEs, CT was higher for DPOAEs, and CS was not different between the two OAE types.

already implied in Figs. 3 and 4, that the PS of the SFOAE is greater than that of the DPOAE in healthy ears. When data from many more normal ears are collected, separate subgroups may emerge within this normal cluster, perhaps related to variations in age, hearing sensitivity, or exposure to noise. Figure 5(B) depicts the relationship between reflection-distortion OAE CT, again confirming that DPOAE magnitude begins to grow compressively at higher stimulus levels than does SFOAE magnitude.

A more familiar measure of response magnitude is seen in the L@CT. Comparing distortion and reflection OAE magnitude at the same fixed stimulus level is problematic because it captures each OAE at different points in its

FIG. 5. The two most informative metrics derived from OAE gain functions, PS and CT, are graphed jointly on an x - y plot; their position in this two-dimensional space elucidates the relationship between reflection and distortion emissions. PS in (A) falls mostly below the diagonal confirming that SFOAEs show greater strength than DPOAEs at this frequency-band (1–2.5 kHz). CT in (B) is above the diagonal for most ears, indicating that response compression occurs at higher stimulus levels for DPOAEs compared to SFOAEs. PS and CT have relatively well-defined clusters describing the normative space for each measure. The vertical and horizontal lines define the 75% interquartile ranges.

dynamic range. Here, we equated response magnitude by the CT. Figure 6(A) shows the result across frequency. At low frequencies, there appears to be little difference between SFOAE and DPOAE magnitude at the compression knee. In contrast, above 2 kHz SFOAE magnitude at CT is significantly higher than that of the DPOAE ($f = 6.48$; $p = 0.012$). Figure 6(B) shows a two-dimensional plot of $L@CT$ for test frequencies between 1 and 2.5 kHz. SFOAE and DPOAE magnitude at CT are relatively equivalent in this low-to-mid frequency band; data points are relatively close to the diagonal and an equal number fall above and below this line.

B. Hearing impairment

Preliminarily, we analyzed DPOAEs in hearing-impaired subjects using a conventional clinical procedure commonly used to screen for and detect hearing loss. This

simplistic analysis was conducted to provide contrast with the more dynamic assessment we propose, and in particular with the combined DPOAE-SFOAE approach. DPOAE magnitude at $L_2 = 65$ dB SPL (commonly employed stimulus levels in audiology clinics) was binned into third-octave intervals between 1 and 4 kHz to derive six frequency-bands; the DPOAE was considered to be present if in an ear if it met two conditions: (1) at least 6 dB SNR was achieved in four of the six frequency bands and (2) amplitude was within ± 2 standard deviations of mean amplitude measured from the normal-hearing group for four of the six frequency bands. Using these criteria, six of eight impaired subjects, would have been identified as clearly hearing-impaired. Two subjects (HI002 and HI004) would have been missed by this thumbs-up/thumbs-down approach to DPOAE analysis, and they would have been classified as normal hearing. However, these two subjects show abnormalities when the joint OAE profile is considered (as reviewed in the sections

OAE Level @ Compression Threshold

FIG. 6. (A) OAE Level at CT ($L@CT$) plotted for SFOAEs (open circles) and DPOAEs (gray squares) across analysis frequency in normal-hearing subjects. A linear regression fit to each OAE separately shows no real difference between the two OAEs in the low-to-mid-frequencies but above 2 kHz, the SFOAE shows higher levels at CT than does the DPOAE. (B) $L@CT$ in a two-dimensional x - y plot. The data cluster around the diagonal indicating that OAE levels normalized by CT are relatively equal for the two OAE types in this low-to-mid frequency range. Bars provide 75% interquartile ranges.

FIG. 7. (Color online) SFOAE (lower panels) and DPOAE spectra (upper panels) shown for five of the eight hearing-impaired ears. Three of those displayed include spectra from both OAE-types in the same ear. The mean noise floor is shown as a dashed gray line. All ears with hearing-impairment had OAEs showing “islands” or frequency-segments of measurable response for at least three stimulus levels, thus allowing for a fit and the calculation of PS, CT, and CS.

that follow). Interestingly, if only SNR is used (with no criteria for OAE magnitude), four of the eight hearing losses would have gone undetected, confirming that the SNR information alone, which is still utilized in many audiology clinics, is not optimal (Gorga *et al.*, 1997). Although the SFOAE is not used in clinical audiology, if we apply the same response criteria to classify SFOAE results in hearing-impaired ears (i.e., 6 dB SNR and response magnitude within ± 2 SD of normative amplitude for 4/6 frequency bands), all eight ears would have been identified as having hearing loss. The SFOAE, even when applied in a rudimentary yes/no manner appears to be more sensitive to mild hearing loss than the DPOAE, at least in this small cohort of ears.

To counter the common assumption that reflection OAEs (and SFOAEs, in particular) cannot be recorded in ears with hearing loss, Fig. 7 presents SFOAE and DPOAE spectra from five of the eight ears with hearing loss at a series of stimulus levels (level denoted by color online). Three of the ears have spectra shown for both SFOAEs and DPOAEs (HI03, HI04 and HI08) and two ears provide one or the other OAE type (HI02, HI07). As evident from this figure, OAEs are present across frequency or in restricted frequency-bands at some or all of the stimulus levels shown in these impaired ears.

We implemented OAE joint-profiling in this group of eight individuals with hearing loss. Figure 8 shows example fits to the SFOAE (black) and DPOAE (gray) gain functions for four hearing-impaired ears at a frequency band of 1–2.5 kHz. The normal fit template is provided as a smaller inset above the data from impaired-ears. One can determine from these four fits to OAEs measured from ears with hearing loss that, although the audiograms are similar (see Fig. 1), the impact of sensory hearing loss on emissions can differ among ears. HI03 and HI04 continued to show stronger SFOAEs than DPOAEs; however, there does not seem to be marked compression in the SFOAE.¹ The hearing loss in subjects HI02 and HI05 produces a reversal in OAE strength; that is, the DPOAE is slightly stronger than the SFOAE in these ears. The fits suggest that cochlear dysfunction disrupted the normal pattern of reflection-distortion OAE features but not in a uniform way across hearing loss, even if audiometrically similar.

Figure 9(A) quantifies the pattern of OAE disruptions in all eight impaired ears using a two-dimensional plot for PS for the frequency band of 1–2.5 kHz (the range for which all impaired ears had measurable OAEs). The data points from impaired ears (filled squares) are numbered to correspond to the audiograms shown in Fig. 1. Data from the normal-

FIG. 8. OAE gain functions and fits (SFOAE – black, DPOAE – gray) are shown for four of the eight hearing-impaired ears. The normal template is provided as a referent (NH). Hearing loss did not disrupt the joint-OAE profile in a uniform manner. HI03 and HI04 continue to show a typical pattern of stronger SFOAEs than DPOAEs but with minimally compressive response growth; HI02 and HI05, in contrast, show equivalent or stronger DPOAEs compared to SFOAEs, which is an atypical pattern.

FIG. 9. (Color online) (A) The joint-OAE profile for PS as a two-dimensional plot at one analysis frequency-band (1–2.5 kHz). Data from all 18 subjects are included. Hearing-impaired ears are designated by filled squares and the subject number is provided for association with audiograms in Fig. 1. (Normal-hearing ears are shown as open circles.) All but one hearing-impaired ear falls outside of the normal range of PS and incipient clusters appear to be present (e.g., HI01, HI04, HI08 and HI07) but too few data are available to confirm this. (B) The joint-OAE profile for CT from all 18 subjects. Four of the eight impaired ears fall outside of the nucleus of normal SFOAE-DPOAE CT. Two ears (HI04, HI06) show strongly elevated DPOAE CT but normal SFOAE CT; another shows the opposite pattern (HI02). HI01 shows elevated CT for both emission types. Not all sensory hearing losses exhibit the same pattern of OAE disruption even though audiograms are similar.

hearing-impaired ears are included as well. As evident in Fig. 9(A), all but one impaired ear shows weakened OAE strength and falls outside of the normal distribution of OAE strength. But the impaired ears are not uniformly affected. HI01, HI07, and HI08 and possibly HI04 show a similar pattern: the DPOAE is more reduced than the SFOAE by hearing loss. HI05 and HI02 likewise show similar disruptions in OAEs: these SFOAEs are more reduced than the DPOAE. With more data, we hypothesize that well-defined clusters will form among a large sample of impaired ears, indicative of common underlying deficits and/or etiologies. Because reflection and distortion OAEs arise via distinct cochlear mechanisms, and appear to be sensitive to distinct cochlear properties, we expect specific cochlear pathologies will produce a “signature” effect on

the joint-OAE profile. For example, a dominant hearing deficit of weakened nonlinearity would theoretically impact the strength of the distortion OAE and show elevated CT but leave the reflection OAE minimally affected. A dominant hearing deficit of broadened tuning might affect the reflection emission maximally while leaving the DPOAE little altered. Further work is warranted with many more hearing-impaired ears to test this hypothesis. Noteworthy is the fact that HI02 and HI04, which were found to be completely normal as per DPOAE clinical assessment, show abnormal PS for both reflection and distortion OAEs.

A joint OAE plot is also shown for CT in impaired ears; data from normal-hearers are included [Fig. 9(B)]. It is evident that SFOAEs and DPOAEs are not identically impacted by hearing loss in any particular ear. Four of the ears fell outside of the normal range of CT values (HI01, HI02, HI04, HI06) and in at least three of these cases, response compression occurred at elevated stimulus levels for DPOAE but not the SFOAE; that is, hearing loss impacted one OAE type (distortion) more than the other (reflection). HI02 and HI04, the two ears showing present and normal “clinical” DPOAE results, both showed abnormally elevated CTs.

OAE level normalized by CT was calculated for each impaired ear and the relationship between SFOAE and DPOAE L@CT was explored in a two-dimensional space (Fig. 10). It is not surprising that OAE magnitude is reduced with hearing loss (as is evident by movement away from the normal cluster and toward the lower left of the diagonal line)—OAE magnitude is known to be negatively correlated with audiometric threshold (Gorga *et al.*, 1993). Other than this reduction in L@CT for four of the impaired ears, the data fall into the normal range and look more or less equivalent for reflection and distortion emissions. Given that this

FIG. 10. (Color online) OAE Level (dB SPL) at CT for SFOAEs and DPOAEs at one analysis frequency-band (1–2.5 kHz). In general, at low-to-mid frequencies, OAE L@CT is comparable for reflection and distortion emissions in normal ears. Four of these eight hearing-impaired ears show reduced L@CT, as noted by movement toward the lower left of the diagonal. However, the OAEs, though reduced in level, retain their relationship in impaired ears and hug the diagonal line. A different pattern of disruption in L@CT might be evident at higher frequencies.

analysis was conducted at low-mid frequencies, and Fig. 6 has already indicated that reflection and distortion OAE levels @ CT are not different in this frequency range, it is not surprising that the data cluster around the diagonal, indicating rough equivalence between the two OAE types with respect to this feature.

Overall the findings of this study indicate three notable results: (1) there is a well-defined normative relationship between reflection and distortion OAE strength and compression features; (2) sensory hearing loss can alter SFOAEs and not DPOAEs (or vice versa), suggesting that reflection and distortion emissions are differently sensitive to underlying deficit and/or etiology; and (3) individuals with sensory hearing loss can have similar audiograms but show different disruptions in the normative reflection-distortion OAE relationship.

IV. DISCUSSION

Otoacoustic emissions can be measured in most normal ears and in ears with sensory hearing loss ranging from slight to moderate. Given the high prevalence of mild-moderate sensory hearing loss and its detrimental effect on development and educational achievement, tools to define and classify mild-moderate cochlear dysfunction would be of great value. The current experiment has taken basic research findings and our now-fundamental knowledge of dual OAE generation mechanisms (Shera and Guinan, 1999; Talmadge *et al.*, 1998; Talmadge *et al.*, 1999; Knight and Kemp, 2000, 2001) and has developed and tested tangible implementations of this core knowledge. Moreover, we have utilized innovative data-collection methods to make this comprehensive OAE protocol feasible. This includes rapid, swept-tone methodology with concurrent, stacked sweep presentation, which reduces testing time significantly. This technique puts a joint-OAE, swept-tone protocol within the reach of scientists and clinicians.

The approach utilized here for OAE assessment is novel in both concept and methodology. First and foremost, it challenges and stretches the conventional audiogram-based taxonomy for hearing loss and focuses instead on deriving information we suspect may be linked to underlying deficit and pathology. This initial experiment represents a proof-of-concept and feasibility study with promising results, but to validate and develop the technique, we must move towards a large-scale study of the joint-OAE profile in hundreds of ears with sensory hearing losses of varied etiologies. This will allow us to better define and understand distinct clusters of joint-OAE features developed here, and to explore the profile of perceptual difficulties associated with each of these profiles.

A. Combined OAE analysis

Unique to our analyses is the consideration of *combined* OAE outcomes to probe the idea that SFOAEs, as reflection emissions, and DPOAEs, as distortion emissions, together are more powerful in defining cochlear function and dysfunction than either considered alone. This notion is based on the understanding that these two classes of OAEs arise

from distinct cochlear mechanisms and hence, are likely to elucidate distinct cochlear properties. Our over-arching research question then is as follows: why measure only one OAE—and why arbitrarily choose between them—if they each provide non-redundant, independent information about cochlear function and dysfunction? It might seem intuitive to use *one* emission, the DPOAE, to study both distortion and reflection together since the total DPOAE contains both elements; however, for most common clinical parameters, the reflection component provides a much smaller contribution to the total DP response than nonlinear distortion. Also, if the DPOAE were to be used for both emission types, independent analysis of both would require separation of the total DPOAE, which is imperfect and renders a low-level reflection component that cannot be reliably associated with any stimulus level; that is, the DPOAE primary tones do not evoke the reflection component, rather the intra-cochlear distortion wave is the stimulus and we cannot measure its strength or intensity. For these reasons, we felt the reflection emission was best generated independently by a single, low-level tone for a more simple, relatively non-confounded measure of reflection. In the future, techniques that interleave SFOAE and DPOAE recordings seamlessly or complex stimuli that evoke both simultaneously would be most effective.

Here, we have shown that mild-moderate sensory losses with similar audiograms do not produce a uniform disruption in the joint-OAE profile, suggesting that the audiogram is insensitive to the underlying deficit in any particular hearing loss; that is, audiometrically similar hearing losses likely encompass varied forms of underlying pathology. We have also shown that reflection and distortion OAEs are not impacted identically by hearing loss, suggesting further that these two OAE classes are differently sensitive to cochlear dysfunction. An example of the first finding is evident in HI03 versus HI06: two mild sensory hearing losses that produce different effects on the joint-OAE profiles. HI03 does not show reduced emission strength or elevated CTs at the test frequencies probed here, but HI06 shows both reduced PS and compression at an elevated level (see Fig. 9). Another such pair is evident in HI08 and HI05. Both show normal CT but HI08 shows strongly reduced OAE strength while HI05 shows only reduced SFOAE strength. This example also supports our second finding: SFOAE strength was reduced in HI05 but DPOAE strength was not. Reflection and distortion OAEs can be differently disrupted by two hearing losses that “look” the same. Similarly, both HI04 and HI06 have elevated DPOAE CTs—a common finding in hearing-impaired ears (Neely *et al.*, 2003; Ortmann and Abdala, 2016)—but the SFOAE CT is within the normal range. Our findings suggest that the combined OAE approach more comprehensively profiles sensory hearing loss, finding atypical patterns that would be otherwise missed if only one or the other were recorded. Another novelty of our approach is that we have discarded the common notion of fixed OAE stimulus parameters determined *a priori* and applied uniformly in every ear for both reflection and distortion OAEs. Instead, the profile is individualized for each ear because we consider the high-resolution spectrum

from each subject in choosing analysis frequencies. Additionally, we generate a level-dependent profile of each OAE and ear and compare OAE magnitude at common landmarks (i.e., re: CT) rather than at the same fixed stimulus dB SPL. This way we are comparing SFOAEs and DPOAEs at points along their own dynamic range. Our novel OAE metrics such as Peak Strength, which depicts the strength of the mechanism generating the response not the magnitude of the response, have further allowed us to equate and compare the two dissimilar OAEs in an effective manner. This strength metric has formed a well-defined cluster in normal ears (Fig. 5) and, also, what appears to be incipient clusters in ears with sensory hearing loss (Fig. 9). Perhaps if we grouped ears with sensory hearing loss by the pattern of their joint-OAE profile, not the audiogram, we would find sub-groups with common etiologies, underlying deficits, and perceptual difficulties.

B. Expanding the joint-OAE profile

These initial findings suggest that otoacoustic emissions can be used in a more comprehensive way to probe features of hearing loss, and that an integrated, joint-OAE protocol may distinguish between hearing losses with different underlying deficits or etiologies. In this study, the joint-OAE profile captured variance among impaired ears that the audiogram failed to capture. In the future, it will be important to firmly define the normative space for this joint-OAE profile with more observations and determine whether hearing-impaired ears generate their own well-defined clusters of combined reflection-distortion emissions features such as PS and CT. The data shown in Fig. 9(A) suggest incipient clusters for joint-OAE strength (HI01, HI04, HI07 and HI08, for example) but many more ears must be tested.

Once clusters are defined in impaired ears, one can probe the similarities that exist among ears showing similar joint-OAE profiles. For example, it is possible that these sub-groupings will elucidate the dominant deficit characterizing a hearing impairment. In a particular ear, for example, compressive growth in the cochlea (i.e., cochlear nonlinearities) may be intact but cochlear gain could be weakened. In this scenario, we would expect that distortion emissions might show strength and compressive growth, but reflection emissions might show reduced strength, similar to the OAE pattern shown by HI05 in Fig. 9(A). One could imagine a future multidimensional tool considering a collective of such joint OAE metrics to define hearing impairment and distinguish among hearing losses.

Including additional OAE features may enhance this type of joint OAE profiling. OAE phase and delay features, for example, which were not considered in the current study, would provide another dimension in the profile. OAE *phase* comprises half of the informative bundle available when recording emissions and to ignore it may limit the emerging picture of cochlear function and dysfunction. Stimulus-frequency OAE delays have been found to correlate with auditory-nerve tuning in laboratory animals (Shera *et al.*, 2010) and with forward-masked psychoacoustic measures of tuning in humans (Shera *et al.*, 2002); therefore, measures of delay may provide a gauge of cochlear tuning in impaired

ears. DPOAE phase has been used as a marker for cochlear scaling symmetry (Dhar *et al.*, 2011; Abdala *et al.*, 2011a; Abdala *et al.*, 2011b) as well as a non-invasive indicator of intra-cranial pressure (Voss *et al.*, 2006). By combining the joint-OAE profile described here with measures of OAE phase and/or delay, a more multi-dimensional tool becomes possible.

In this initial feasibility study, we have not probed perceptual performance and therefore cannot link perception to the joint-OAE profile. However, this is another future step that will help us better understand reflection-distortion OAE patterns emerging in two-dimensional (or multi-dimensional) space. PS and CT, and the clusters they form in the joint-OAE profile, may be associated with characteristic perceptual profiles. One could imagine the utility of an objective test that predicts specific perceptual difficulties. Will individuals with compromised cochlear compression experience steep growth of loudness? Preliminary evidence suggests this could be the case (Ortmann *et al.*, 2017). Will children with shortened SFOAE delays have broadened tuning curves and hence, struggle to hear in noisy environments such as classrooms? Future work will do well to characterize how an atypical joint-OAE profile correlates with an associated perceptual profile and determine whether common joint OAE profiles [i.e., HI01, HI04, HI07, and HI08 in Fig. 9(A)] show common perceptual profiles.

Otoacoustic emissions have been applied in clinics and laboratories for the last 20 years, mostly in a rudimentary manner with the objective of *detecting* hearing loss. This study and others like it aim for a fuller utilization of the unique information embedded in OAEs. Supported by the promising findings here, we hypothesize that reflection and distortion emissions have *distinct sensitivities* to various forms of sensory hearing loss, which may be useful in predicting the dominant underlying hearing deficit in individual ears. Exploiting knowledge of OAE generation mechanisms to describe hearing deficits and predict perceptual difficulties may be a realistic goal with further study. Defining the dominant underlying deficit in impaired ears, be it weakened cochlear compression or broadened cochlear filters or a combination, could eventually lead to more targeted intervention strategies and individualized fitting of auditory prostheses.

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¹The CT was assigned in these subjects as an “at least” value equivalent to the highest stimulus level presented because the fit could not reliably estimate the CT.

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