Published in final edited form as:

AIP Conf Proc. 2015 ; 1703: . doi:10.1063/1.4939413.

Exploiting Dual Otoacoustic Emission Sources

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Abstract

Two distinct processes generate otoacoustic emissions (OAEs). *Reflection-source* emissions, here recorded as stimulus frequency OAEs, are optimally informative at low sound levels and are more sensitive to slight hearing loss; they have been linked to cochlear amplifier gain and tuning. *Distortion-source* emissions are strongest at moderate-high sound levels and persist despite mild hearing loss; they likely originate in the nonlinear process of hair cell transduction. In this preliminary study, we exploit the unique features of each by generating a combined reflection-distortion OAE profile in normal hearing and hearing-impaired ears. Distortion-product (DP) and stimulus-frequency (SF) OAEs were recorded over a broad range of stimulus levels and frequencies. Individual I/O and transfer functions were generated for both emission types in each ear, and OAE peak strength, compression threshold, and rate of compression were calculated. These combined SFOAE and DPOAE features in normal and hearing-impaired ears may provide a potentially informative and novel index of hearing loss. This is an initial step toward utilizing OAE source in characterizing cochlear function and dysfunction.

INTRODUCTION

Different types of otoacoustic emissions (OAEs) carry different information about cochlear function [11]. The dual-source model of OAE generation suggests that while distortion emissions (i.e., the distortion component of DPOAEs) are best suited to probe the strength and form of the cochlear nonlinearity underlying their origin, reflection emissions (i.e., stimulus frequency, click-evoked OAEs) best probe the gain of the cochlear amplifier and cochlear tuning [12]. Furthermore, the framework suggests that distortion emissions should be optimally evoked by moderate-high stimulus levels where cochlear nonlinearities become evident. In contrast, reflection emissions will be most sensitive to changes in cochlear status at low stimulus levels where the cochlear amplifier is most effective. The potential value of this mechanistic framework is that each of the two emission types—though similar in some of their dependencies and subject to common influences of cochlear amplification—reflects distinct cochlear properties, properties that may be affected differently among ears with sensorineural hearing loss (SNHL). Using either reflection- or distortion-source OAEs in isolation could limit scientific and diagnostic information. At present, *SNHL* is a catch-all label referring to auditory deficits of uncertain etiology and form. Whether a hearing loss predominantly impacts predominantly the compressive features of the cochlea and/or mechanical tuning and gain of the cochlear amplifier is not probed when SNHL is diagnosed.

Research has shown that reflection- and distortion-source emissions provide non-redundant information and can be independently altered by natural processes such as maturation and aging [1,2], as well as experimental manipulations, such as aspirin [10] or activation of the medial efferent reflex [3]. Additionally, the two emission types show different sensitivities to hearing loss [4,9]. By recording a combined reflection-distortion OAE profile in normal and impaired ears, groupings of ears with similar auditory deficits may emerge. We hypothesize that the normal ear has a typical OAE signature of reflection-distortion energy, and sensory damage will disrupt this typical signature in a systematic way depending on the deficit. Rather than consider SNHL as a homogeneous and unitary category, the possibility exists that auditory deficits can be differentiated to some extent. Here, we present a strategy for exploiting the distinct properties embodied by distortion- and reflection-source to improve measures of cochlear function and dysfunction.

METHODS

Distortion-source OAEs (unmixed DPOAEs) at $2f_1-f_2$ and reflection-source OAEs (SFOAEs) were measured from 0.5 to 8 kHz using custom-designed systems with a swept-tone stimulus presentation [7, 8]. DPOAEs were recorded with a fixed f_2/f_1 of 1.22 and L_2 ranging from 30 to 85 dB SPL; SFOAEs were recorded by interleaved suppression [e.g., 6] with probe tones presented from 20 to 50 dB SPL. MATLAB-based software (inverse FFT) was applied offline to unmix the DPOAE and isolate the distortion component based on phase-gradient delays. (Note: In this report, “DPOAE” always refers to distortion component only, as reflection components have been eliminated.) OAE level and phase were calculated using a least-squares-fit algorithm [7, 8]. Both SF and DPOAEs were recorded across a large parametric space to characterize the level-dependent growth of each. Figures 1A, D show a family of SF and DPOAE spectrograms in one normal-hearing ear. Frequency bands (~100 Hz wide) were identified at local peaks in the SFOAE spectrum and Input/Output functions were constructed at these target frequencies for each emission type. The test frequency illustrated in panels 1B and E is 1.8 kHz. OAE magnitudes in this ear grow linearly at low levels and compressively at higher levels. Such compression is more intuitively visualized, and comparison between emissions facilitated, when amplitude is normalized by stimulus level as shown in panels 1C and F. We refer to these stimulus-normalized responses as effective transfer functions [6]. Three features were extracted from each transfer function: (1) *Peak strength* of the emission or $\text{Peak}_{\text{SF,DP}}$ (in dB). The *peak strength* index, unlike conventional measures of OAE magnitude, depicts the growth of the response measured from the low-level linear region and not simply the highest emission level in dB SPL; (2) *compression threshold* or $\text{CT}_{\text{SF,DP}}$ (in dB SPL) which is the level at which the emission starts to grow compressively; and (3) $\text{Slope}_{\text{SF,DP}}$ (in dB/dB) which is the rate of compression derived from the downward-sloping segment at moderate-high stimulus levels.

PRELIMINARY RESULTS

A fit of the form $T(A) = \text{Peak}/(1+(A/\text{CT})^s)$ where A is stimulus pressure, CT is compression threshold in units of pressure and s is the slope of the compressed region, was used to extract the three features from each transfer function. The fits are illustrated by thick (SF) and thin (DP) black lines in panels 1C and F. Figure 2 illustrates a normative template of fits and SF

and DPOAE features collected from a normal-hearing ear. SFOAE *peak strength* is greater than DPOAE *peak strength*, and the DPOAE compression threshold occurs at higher stimulus levels than the SFOAE compression threshold. These two observations were consistent in all normal-hearing subjects tested thus far; this pattern may define the normal ear. Recording SF and DPOAEs in normal and impaired ears is ongoing in our laboratories to further characterize the typical distribution of reflection and distortion features as well as their relational features. Additionally, we aim to define how cochlear dysfunction disrupts this normal pattern, possibly allowing for insight into underlying deficits.

The four hearing-impaired ears shown in Figure 3 manifest different patterns of reflection and distortion OAE disruption although the audiograms are similar. We have provided values for only the *peak strength* feature in Fig. 3. The subject in panel 3C shows little disruption of the general relationship between reflection and distortion emissions though OAEs are reduced overall: The SFOAE still generates greater *peak strength* and the DPOAE *compression threshold* is still higher than that of the SFOAE. In contrast, the ear in panel 3D shows an oft-reported response to mild SNHL, namely that reflection emissions are more sensitive to mild loss than DPOAEs. Accordingly, SFOAE *peak strength* is more reduced than DPOAE *peak strength* in panel 3D. The subject in Panel 3B displays an atypical pattern: the distortion emission has dropped much more than the reflection emission though both are reduced. *These four ears indicate that SNHL of generally similar degree and configuration (mild-sloping) can produce varying effects on OAE sources.*

DISCUSSION

Here we have introduced a strategy for measuring a combined SF-DP OAE profile that considers the distinct nature of emissions arising by two different mechanisms: linear reflection and nonlinear distortion. Importantly, with this work we aim to expand beyond the goal of *detecting* hearing loss with OAEs, and seek to *describe* the nature of hearing deficits, pushing the conventional taxonomy for SNHL. In addition to generating descriptive statistics to define measures of central tendency and variability for the three SFOAE and DPOAE features in each ear, we will search for groupings or clusters of ears with similar results as part of our analysis.

When a sufficient number of combined SF-DP OAE profiles have been collected (our target is between 200–300), exploratory latent profile analyses (LPA) will be applied. This is a statistical tool that identifies the number of classes (and sub-clusters) explaining the greatest amount of variance in a large pool of data. Each SF and DPOAE feature, Peak, CT and Slope, will undergo this sort of cluster analysis. The LPA determines the percentage of variance accounted for by each class, provides a goodness of fit measure and assigns a *p* value. A cluster of ears showing similar SF-DP OAE features may share a common deficit; that is, OAE source may distinguish between a SNHL involving a dominant dysfunction in nonlinearity versus cochlear amplification. Additionally, if clusters are detected, recording parameters will be pared to the minimal set required to preserve cluster identification with the aim of generating a clinically feasible tool in the future.

Figure 4 presents one method for visualizing reflection-distortion OAE clusters. Here we highlight the *peak strength* measure which may be the most informative and most likely to be extracted from the greatest number of hearing-impaired ears even when other features cannot be measured due to abbreviated I/O functions in this cohort. Figure 4 depicts hypothetical clusters of data (ellipses, circle) illustrating the relationship between Peak_{SF} and Peak_{DP} . The figure also plots actual data from seven subjects tested with the OAE experimental protocol in one frequency range ($f = 1.3\text{--}1.6$). A mean value derived from fits to OAE data in a small group of normal hearers ($n = 14$) that contributed either a DPOAE or SFOAE is shown as a small open circle with SEM. The stars and filled circles depict 7 ears tested with our full experimental protocol. The stars are normal-hearers and the filled circles are data from four hearing-impaired subjects shown in Fig. 3. As suggested by the stars (and mean value), a normal healthy cochlea produces measureable and robust distortion and reflection OAEs with stronger *peak strength* for reflection. This normal cluster falls just below the diagonal line in the upper right quadrant. In a cochlea with compromised nonlinearity *and* a weakened cochlear amplifier, one might see data clustering in a space depicted by the large circle along the diagonal line (lower left quadrant); that is, both types of emissions show reduced strength. The ellipse in the upper left quadrant depicts a hypothetical cluster of data points observed in ears with intact cochlear nonlinearity but weakened cochlear amplifier gain. In clinical accounts and large-scale studies, it is often reported that DPOAEs are measureable even when CEOAEs, a reflection-source emission, are not; CEOAEs appear to be more sensitive to mild SNHL [4, 9]. Finally, although likely rare in humans, the cluster in the lower right quadrant of Fig. 4 may represent an ear with intact sensitivity and tuning but an extended linear range of function, much like the deficit hypothesized in Shera and Abdala [13]. The STRC-deficient mutant mouse [14] shows absent DPOAEs at birth and although measurements of reflection-type emissions have not been attempted in this transgenic mouse, compound action potential (CAP) thresholds and tuning curves are near normal early in life. This combination suggests reduced cochlear nonlinearity coupled with a functional cochlear amplifier.

Figure 4 presents gross clusters predicted from anecdotal clinical reports, large-scale studies and mutant mouse models; however, with data from a large cohort of normal and hearing-impaired human ears, we expect that more nuanced groupings will emerge among these quadrants, further delineating the deficits associated with SNHL. This combined reflection-distortion approach to describing cochlear function and dysfunction has not been attempted or studied and its utility in describing auditory deficits is unknown. We believe it to be an important and testable empirical question for future research and optimistically, for eventual clinical application.

Acknowledgments

This work was supported by grants from the National Institutes of Health (R01 DC03552, P30 DC010743) and by the University of Southern California. We thank Srikanta Mishra, Mahnaz Ahmadi, and Jasmine Siudzinski for assistance with data collection and Christopher Shera and Ping Luo for system development and helpful discussions.

References

1. Abdala C, Dhar S. Distortion product otoacoustic emission phase and component analysis in human newborns. *J Acoust Soc Am*. 2010; 127:316–325. [PubMed: 20058979]
2. Abdala C, Dhar S. Maturation and aging of the human cochlea: a view through the DPOAE looking glass. *J Assoc Res Otolaryngol*. 2012; 13:403–421. [PubMed: 22476702]
3. Abdala C, Mishra SK, Williams TL. Considering distortion product otoacoustic emission fine structure in measurements of the medial olivocochlear reflex. *J Acoust Soc Am*. 2009; 125:1584–94. [PubMed: 19275316]
4. Gorga MP, Neely ST, Bergman BM, Beauchaine KL, Kaminski JR, Peters J, Schulte L, Jesteadt W. A comparison of transient-evoked and distortion product otoacoustic emissions in normal-hearing and hearing-impaired subjects. *J Acoust Soc Am*. 1993; 94:2639–2648. [PubMed: 8270740]
5. Kalluri R, Shera CA. Near equivalence of human click evoked and stimulus frequency emissions. *J Acoust Soc Am*. 2007; 121:2097–2110. [PubMed: 17471725]
6. 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]
7. Kalluri R, Shera CA. Measuring stimulus frequency otoacoustic emissions using swept-tones. *J Acoust Soc Am*. 2013; 134:356–368. [PubMed: 23862813]
8. Long GR, Talmadge CL, Lee J. Measuring distortion product otoacoustic emissions using continuously sweeping primaries. *J Acoust Soc Am*. 2008; 124:1613–1626. [PubMed: 19045653]
9. Miller JAL, Marshall L, Heller LM. A longitudinal study of changes in evoked otoacoustic emissions and pure-tone thresholds as measured in a hearing conservation program. *Intl J Audiol*. 2004; 43:307–322.
10. Rao A, Long GR. Effects of aspirin on distortion product fine structure: interpreted by the two-source model for distortion product otoacoustic emissions generation. *J Acoust Soc Am*. 2011; 129:792–800. [PubMed: 21361438]
11. 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]
12. Shera CA, Guinan JJ Jr, Oxenham AJ. Revised estimates of human cochlear tuning from otoacoustic and behavioral measurements. *Proc Nat Acad Sci USA*. 2002; 99:3318–3323. [PubMed: 11867706]
13. Shera, CA.; Abdala, C. Otoacoustic emissions—Mechanisms and Applications. In: Tremblay, K.; Burkard, R., editors. *Translational Perspectives in Auditory Neuroscience*. San Diego: Plural Press; 2012. p. 123–160.
14. Verpy E, Masmoudi S, Zwaenepoel ML, Leibovici M, Hutchin TP, Del Castillo I, Nouaille S, Blanchard S, Lainé S, Popot JL, Moreno F, Mueller RF, Petit C. Mutations in a new gene encoding a protein of the hair bundle cause non-syndromic deafness at the DFNB16 locus. *Nat Genet*. 2001; 29:345–349. [PubMed: 11687802]

FIGURE 1.

A, D: Level series of SFOAE and unmixed DPOAE (i.e., distortion component) spectrograms in the same normal-hearing ear. B, E: OAE Input/Output functions for each emission type at $f \approx 1.8$ kHz (denoted by arrows in A, D). Only points with SNR > 6 dB were included. C, F: OAE magnitude normalized by stimulus level, i.e., converted into transfer functions. Fits to SFOAE and DPOAE transfer functions are shown by thick (SF) and thin (DP) black lines in panels C and F. Three features are derived from each transfer function as illustrated in panel C: *peak strength*, *compression threshold* and *slope*.

FIGURE 2.

DPOAE and SFOAE transfer functions from one normal hearing ear. The normal transfer function shows greater SFOAE peak strength and higher DPOAE compression thresholds.

FIGURE 3.

The SFOAE and DPOAE transfer functions and fits (thick line = SFOAE; thin line = DPOAE) from four ears with slight to mild-moderate SNHL. The gray area of the audiogram represents the region of normal hearing (< 15 dB HL); the dashed line is at 0 dB HL. Even though the degree and configuration of SNHL does not vary greatly among individuals, the disruption of reflection and distortion-source OAEs does vary among ears. See text for further description of the OAE features extracted from these hearing-impaired ears.

FIGURE 4.

The relationship between *Peak Strength* of the SFOAE and DPOAE feature is displayed. The various large ellipses and circle represent hypothetical boundaries of clusters that could emerge after a large cohort is tested. The small open circle displays the mean of *Peak Strength* calculated from fits to group data (SFOAE, $n = 8$; DPOAE, $n = 6$). The filled stars are results from three normal-hearing subjects tested with the proposed experimental protocol. The filled circles are results from the 4 hearing-impaired ears tested with the experimental protocol and displayed in Fig. 3.