Estimates of Cochlear Compression Using Distortion Product Otoacoustic Emissions and Growth of Forward Masking

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Objective: The authors investigated the relationship between behavioral and physiologic estimates of cochlear compression.

Design: Cochlear compression was estimated in distortion product otoacoustic emission (DPOAE) fine structure minima and maxima near 4 kHz. The composite DPOAE response and separated generator and reflection components yielded three estimates in four young adults with normal hearing. DPOAE estimates were compared to behavioral compression estimates derived using a growth of forward masking (GOFM) paradigm. The DPOAE primary tone f_2 and GOFM signal were identical and selected individually based on placement in a DPOAE fine structure minimum.

Results: Across participants, DPOAE compression estimates derived from the generator component were most similar to estimates derived from the GOFM paradigm and did not vary with DPOAE fine structure.

Conclusions: These results suggest that the generator component may provide a quick, reliable estimate of cochlear compression in humans. This may prove useful in populations that cannot give behavioral responses.

Key words: Cochlear compression, Distortion product otoacoustic emission, Distortion product otoacoustic emission fine structure, Growth of forward masking.

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INTRODUCTION

The healthy basilar membrane (BM) in mammals responds to midlevel acoustic stimuli in a compressive, nonlinear fashion. Conversely, damaged cochleae often exhibit reduced or absent nonlinearity. This has been shown using intracochlear recordings in animals (Ruggero et al. 1997) and using noninvasive techniques with human participants (Oxenham & Plack 1997; Dorn et al. 2001). However, full understanding of the human BM input–output response is lacking. Previous studies examining relationships between estimates of cochlear compression derived from distortion product otoacoustic emissions (DPOAE) and behavioral paradigms in the same individuals have shown conflicting results (Williams & Bacon 2004; Johannesen & Lopez-Poveda 2008).

Discrepancies in the existing literature may be due, in part, to basing DPOAE compression estimates on the composite DPOAE response. Shera and Guinan (1999) discuss two separate mechanisms that give rise to otoacoustic emissions (OAE): linear reflection (OAE reflection component) and nonlinear distortion (OAE generator component). The reflection component produces a phase-frequency function with a rapidly rotating phase (modeled as reflections from fixed inhomogeneities along the BM). Conversely, the generator component phase remains fairly constant across frequency. Vector addition of the acoustic waves in the ear canal results in constructive and destructive interference, producing maxima and minima in DPOAE responses across frequency, termed DPOAE fine structure. Separating the distortion and reflection components, using methods such as a least squares fit analysis, may produce compression estimates that are more closely related to behavioral responses. Because fine structure differs across individuals, estimating compression at a common frequency (e.g., 4000 Hz) for every participant may result in DPOAE estimates derived from different points in the fine structure (e.g., a minimum for one individual may be in the vicinity of a maximum for another).

This study builds on prior work examining relationships between physiologic and behavioral compression estimates. Specifically, the purpose of this study was to investigate the effects of DPOAE fine structure on the relationship between compression estimates obtained using DPOAEs and a growth of forward masking (GOFM) paradigm.

MATERIALS AND METHODS

Participants

Four females (age 19–28 years) with normal hearing participated. Inclusion in the study required robust DPOAE fine structure near 4 kHz, which was screened at an L2 level of 60 dB SPL. The ear with more robust fine structure near 4 kHz served as the test ear (1 right ear, 3 left ears).

DPOAE Stimuli and Procedure

DPOAEs were collected using 4 sec/octave, logarithmically sweeping primaries at a fixed f_2/f_1 ratio of 1.22. Levels were set at $L_1 = 0.4L_2 + 39$ dB (Kummer et al. 1998) for each L_2 tested (50 to 70 dB SPL in 5 dB steps) to limit frequency shifts in DPOAE fine structure with level (Cooper & Kemp 2009). Levels were chosen to coincide with the range of maximum compression (Neely et al. 2003). DPOAE amplitude was measured at $2f_1 - f_2$. The f_2 tone was swept from 1500 to 6000 Hz to capture DPOAE fine structure at frequencies used for both signals in the GOFM task (i.e., signal and masker tone at ~4 and ~2 kHz, respectively), using the method from Long et al. (2008). Probe fit was verified at the beginning, middle, and end of the session with a white noise to ensure consistency of probe placement throughout testing.

Averaged DPOAE data were analyzed using the least squares fit procedure (Long & Talmadge 1997) to separate the generator and reflection components. Data were also analyzed using a custom MATLAB (version 7.0.4) program to identify significant

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DPOAE fine structure minima and maxima. To qualify as a significant minimum or maximum, DPOAE level, depth, and frequency spacing were measured using criteria from Abdala and Dhar (2010).

DPOAE Estimates of Compression

Compression was estimated from the slopes of DPOAE input/output (I/O) functions. DPOAE I/O functions were plotted as a function of f_2 level (50–70 dB SPL) and were fit using linear regression. I/O functions were plotted using the level of f_2 because the distortion product originates from the maximum overlap region of the primary frequencies, which is nearer the f_2 place. Compression estimates were then derived from the slope of the I/O function (Neely et al. 2003). Compression was estimated at the f_2 frequency corresponding to the fine structure minimum nearest 4 kHz for each participant. DPOAE fine structure minima (as opposed to maxima) were studied based on the findings that loudness compression was greatest in hearing threshold fine structure minima (Mauermann et al. 2004) and that similarities exist between DPOAE and behavioral threshold fine structure (Talmadge et al. 1998).

The frequency minima used to estimate compression shifted slightly with intensity; however, compression was estimated at a single, fixed frequency near the minima. This frequency was selected as the arithmetic mode of the set of frequencies corresponding to the peaks of fine structure minima across the shift in intensities. When the mode was unavailable, the median was used (participant S2). The average absolute deviation from the fixed frequency chosen for testing across participants was 38.2 Hz. The largest shift ranged from −62 to 255 Hz for S2 and the smallest change ranged from −33 to 0 Hz for S4. Compression was also estimated for the generator and reflection components at the same frequency minimum. Additionally, these three estimates (i.e., composite, generator, and reflection) were derived from an f_2 frequency corresponding to a DPOAE fine structure maximum, also using the mode and median of the frequency set. The maximum was chosen as the greater of the two peaks immediately surrounding the fine structure minimum.

GOFM Stimuli and Procedure

The GOFM signal frequency (f_s) was the same fixed frequency located at the minima nearest 4 kHz for each participant used to estimate DPOAE compression. Signal levels were presented at 50, 55, 60, 65, and 70 dB SPL. GOFM curves were measured using an on-frequency ($f_m = f_s$) and off-frequency ($f_m \approx 0.5 \times f_s$) masker. Both the signal and masker tones were gated with raised-cosine ramps of 2.5 ms. Steady state portions were 0 and 100 ms for the signal and masker, respectively. The silent interval between zero-points in the envelopes of the offset of the masker and onset of the signal was 0 ms. A Gaussian, high-pass filtered noise was presented at a spectrum level 40 dB below the spectrum level of f_s throughout the task to minimize off-frequency listening. Thresholds were obtained using an adaptive two-alternative forced choice procedure and 3 dB step size. A two-up, one-down stopping rule was used to track the 70.7% correct point of the psychometric function (Levitt 1971).

GOFM Estimates of Compression

On- and off-frequency masker levels were plotted as a function of signal level. A best fit to the data in each function was obtained using linear regression. Slope values were calculated from the best fit functions and used to estimate cochlear compression by taking the ratio of the off- and on-frequency slopes (Oxenham & Plack 1997). Use of alternative fitting functions (e.g., polynomial) did not substantially improve the fit to our data.

RESULTS

DPOAE data were analyzed as three components: the composite response, the reflection component, and the generator component. Figure 1 shows these components for participant S1 and is representative of results obtained from all study participants.

Compression estimates varied substantially across participants and methods. Figure 2 shows DPOAE compression estimates for composite and generator responses (top and bottom panels, respectively) from fine structure minima and maxima plotted as a function of GOFM estimates. Across participants, compression estimates from the GOFM paradigm were very similar to estimates obtained from the DPOAE generator component. Larger differences were observed between GOFM estimates and those derived from the composite DPOAE response.

Compression estimates derived from a fine structure maximum (Fig. 2, open symbols) in the DPOAE composite response consistently showed more compression than GOFM estimates. In contrast, consistently less compression than GOFM was observed when compression estimates based on the composite DPOAE were derived from a fine structure minimum (closed symbols). Paired sample *t*-tests were used to compare these differences (Table 1). The GOFM compression estimate (Mean (M) = 0.36 dB/dB, standard error (SE) = 0.054) was significantly different ($t(3) = 11.48$; $p = 0.0014$, $d = 0.98$) from the mean estimate based on the DPOAE composite response obtained in a fine structure maximum (M = 0.24 dB/

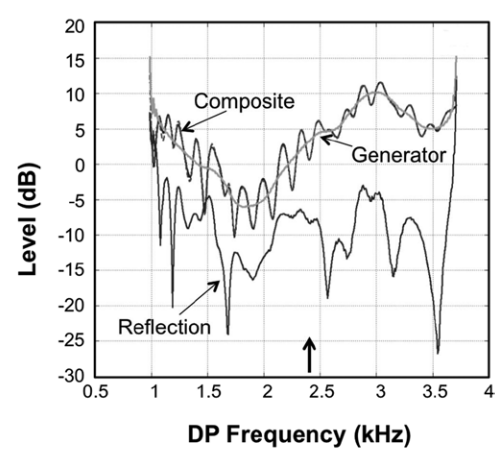

Fig. 1. Distortion product otoacoustic emission (DPOAE) magnitude plotted as a function of cubic distortion product frequency for S1. The smooth, light gray line shows the generator component amplitude; the dark, quasiperiodic line overlapping the generator component shows the composite response amplitude; the bottommost line with greater maxima and minima shows the reflection component amplitude. The bold arrow along the abscissa indicates the DPOAE frequency corresponding to an f_2 frequency of 3773 Hz, where DPOAE and growth of forward masking estimates of compression were derived for S1.

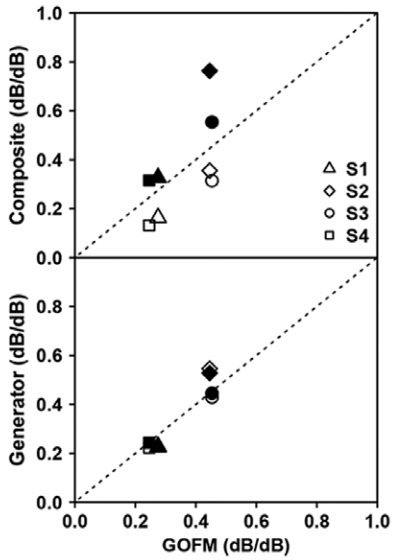

Fig. 2. Distortion product otoacoustic emission (DPOAE) composite response and generator component estimates of compression (top and bottom panels, respectively) plotted as a function of growth of forward masking (GOFM) estimates for each participant. Closed symbols are estimates from DPOAE fine structure minima; open symbols are estimates from fine structure maxima.

dB, SE = 0.056). The DPOAE compression estimate based on a fine structure minimum (M = 0.49 dB/dB, SE = 0.104) was substantially larger than the GOFM compression estimate, although the difference did not reach statistical significance ($t(3) = 2.18$; $p = 0.11$, $d = 0.78$). The lack of statistical significance for data in a fine structure minimum coupled with a large effect size (Cohen's d) suggests this comparison was underpowered. This was confirmed via post hoc power analyses (power = 0.207). However, the large effect sizes across both comparisons suggest the differences observed between methods are meaningful.

Conversely, compression estimates from the DPOAE generator component did not vary based on position in fine structure (i.e., minima or maxima) and were very similar to GOFM compression estimates. Indeed, there was no significant difference between mean GOFM and generator estimates in either the minimum (M = 0.36 dB/dB, SE = 0.15; $t(3) = 0.22$; $p = 0.83$, $d = 0.0$) or maximum (M = 0.36 dB/dB, SE = 0.15; $t(3) = 0.02$; $p = 0.98$, $d = 0.0$) conditions (Table 1).

Compression estimates derived from the reflection component seem to be related to neither GOFM nor other DPOAE composite or generator compression estimates. This is consistent with the hypothesis that the reflection component is influenced mostly by inhomogeneities along the BM (Talmadge et al. 1999).

DISCUSSION

Previous studies have examined the relationship between cochlear compression estimates derived from DPOAEs and a psychophysical paradigm in the same individuals (Williams & Bacon 2004; Johannesen & Lopez-Poveda 2008). Williams and Bacon found strong correlations at all frequencies tested (1000, 2000, and 4000 Hz) using the unseparated DPOAE response and temporal masking curves (TMCs). Johannesen and Lopez-Poveda applied an averaging technique to the composite DPOAE response to reduce the influence of DPOAE fine structure. They found a strong correlation between DPOAE and TMC estimates of compression at 4000 Hz but not at 500 or 1000 Hz.

These preliminary data are consistent with the existing literature in showing a relationship between compression estimates at high frequencies derived from a psychophysical paradigm and the composite DPOAE response, although systematic differences between methods were apparent (Fig. 2). The closest agreement in compression estimates was between the generator component and GOFM. Indeed, this was hypothesized based on the findings of Shera and Guinan (1999). They showed that the generator and reflection components arise not only from separate locations along the BM (i.e., the f_2 and distortion product places), but from different mechanisms as well (a distortion source and coherent reflection, respectively). This suggests that focusing on growth of the DPOAE distortion source (i.e., the generator component) would yield an accurate physiological estimate of cochlear compression by minimizing the role of coherent reflection. The stimuli used to derive estimates of cochlear compression during our GOFM task are presented sequentially (not simultaneously like DPOAE stimuli), which inherently limits interaction between the tones. GOFM responses are thus less likely to be impacted by interactions with reflections. Therefore, it is reasonable to postulate the DPOAE generator component estimates would have the highest correlations with the GOFM estimates compared to both the reflection and composite responses.

This hypothesized trend appeared near 4000 Hz, where DPOAE fine structure is less pronounced (Abdala & Dhar 2010). Should this trend continue at lower frequencies (e.g., below 2000 Hz), where DPOAE fine structure is more robust, use of the separated generator component may provide compression estimates

TABLE 1. Test frequencies (Hz) and DPOAE and GOFM compression estimates (dB/dB)

	Test Frequencies (Hz)		Composite		Generator		GOFM
Subject	Minimum	Maximum	Maximum	Minimum	Maximum	Minimum	Minimum
S1	3773	3992	0.16	0.33	0.23	0.23	0.28
S2	3567	3724	0.36	0.76	0.55	0.53	0.45
S3	3757	3889	0.31	0.55	0.43	0.45	0.45
S4	3839	3991	0.13	0.32	0.22	0.24	0.25
Average			**0.24***	0.49	0.36	0.36	0.36

Test frequency columns describe the DPOAE minimum and maximum frequencies used for deriving DPOAE compression estimates. DPOAE compression estimates were obtained from the composite response and generator component at both a fine structure minimum and maximum. GOFM estimates were measured at the fine structure minimum test frequency. Bolded values with an asterisk are significantly different from the GOFM compression estimate.

DPOAE, distortion product otoacoustic emission; GOFM, growth of forward masking.

highly correlated with behavioral estimates and work toward reconciling the disparity in the literature. This is an exciting possibility, as DPOAEs are suitable for laboratory and clinical use because of the rapid nature of data collection (i.e., minutes). Further, as a physiological test, DPOAEs can be used in populations unable or unwilling to respond. The versatility of data collection and potential accuracy of compression estimates from the generator component might eventually lead to augmented hearing aid fitting strategies (e.g., NAL-NL2, DSL v5.0) for uncooperative populations (Müller & Janssen 2004). Diagnostically, Mauermann et al. (1999) have suggested that changes in DPOAE fine structure in persons with mild hearing loss are dominated by the reflection component and are thus more sensitive to mild hearing loss than overall amplitude of DPOAE responses. Additionally, Shera and Guinin (1999) point out the potential utility of separating DPOAE components to examine cochlear pathologies specific to their different sources and mechanisms of generation.

Future work to expand on these preliminary data should include (1) testing at lower frequencies, (2) testing over more intensities, (3) replicating these results with other behavioral paradigms (e.g., TMCs), and (4) investigating these results in persons with hearing loss.

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