The effects of window delay, delinearization, and frequency on tone-burst otoacoustic emission input/output measurements

Michael Epstein[a] and Søren Buus
Institute of Hearing, Speech & Language and Communications & Digital Signal Processing Center,
Electrical & Computer Engineering Department (440 DA), Northeastern University,
Boston, Massachusetts 02115

Mary Florentine
Institute of Hearing, Speech & Language and Department of Speech-Language Pathology & Audiology
(106/A FR), Northeastern University, Boston, Massachusetts 02115

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Tone-burst otoacoustic emissions (TBOAEs) are a potential tool for objectively examining cochlear activity in humans. However, their use requires knowledge of how the TBOAE input/output depends on measurement and analysis paradigms. The present experiment examined the effect of variations in response-window timing, response delinearization, and local changes in stimulus frequency on TBOAE input/output measurement. None of these experimental manipulations had a profound effect on TBOAE measurements as long as reasonable parameter choices were made. Nonetheless, judicial choice of the experimental parameters can optimize the assessment of BM I/O functions. It is concluded that the consistency of TBOAE I/O across the parameters tested makes it a viable tool to consider for examining human cochlear activity. © *2004 Acoustical Society of America.* [DOI: 10.1121/1.1768254]

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I. INTRODUCTION

Otoacoustic emissions have been used to examine a variety of phenomena such as cochlear tuning (Shera *et al.*, 2002), critical bandwidth (Neumann *et al.*, 1997), and noise-hazard responses (Mansfield *et al.*, 1999). Otoacoustic emissions may also provide a noninvasive means for assessing some of the finer details of cochlear processing. The present experiment seeks to determine how stimulus and measurement parameters affect tone-burst otoacoustic emission measurements. This will provide some insight into whether or not they are consistent enough across measurement parameters to act as a potential tool for the assessment of cochlear activity.

Withnell and Yates (1998) first suggested the use of otoacoustic emissions to examine basilar-membrane nonlinearity. They were especially interested in identifying the level at which compression of the function begins, i.e., the compression threshold. Their work primarily used distortion-product otoacoustic emissions (DPOAEs) in guinea pigs. Buus *et al.* (2001) used DPOAEs to determine basilar-membrane I/O functions in humans, but they found that complexities associated with DPOAEs made it difficult to achieve their goal. For example, it is not possible to determine BM I/O functions using DPOAE measurements at high levels where the presence of multiple components is likely to lead to suppression. Suppression is likely to obscure the relationship between basilar-membrane vibration amplitude and otoacoustic emissions. In addition, low-frequency measurements cannot be performed because of noise-floor considerations. Due to such difficulties with DPOAEs, it seemed that TBOAEs might be a better choice for basilar-membrane I/O assessment in humans. Preferably, measures of TBOAEs should be made in a strong OAE-producing frequency region where the signal-to-noise ratio is high.

Previous studies using transient-evoked otoacoustic emissions (TEOAEs) hint at the potential for the use of TBOAEs for studying level-dependent amplification within the auditory system and for comparing results with psychoacoustic measures (Norton and Neely 1987; Neumann *et al.*, 1997). Although these studies do not specifically examine basilar-membrane mechanics, the data show input-output relations that resemble basilar-membrane I/O functions measured in animals. Thus, a quantitative understanding of TEOAE generation may provide a simple and direct method for assessing basilar-membrane I/O functions and their dependence on stimulus frequency.

Before any examination of tone-burst otoacoustic emissions as a potential means of determining basilar-membrane input-output functions or any other cochlear function can be performed, it is necessary to devise an effective technique for measuring the tone-burst otoacoustic emissions and to show that estimates of the I/O function are largely independent of specific choices of measurement parameters. To this end, a frequency at which the tone-burst otoacoustic emissions can easily be measured must be determined. Tone-burst OAEs might be useful in the assessment of cochlear function only if (1) the measurements can be obtained for a large range of input levels, (2) the outcome is largely independent of specific choices of stimulus and measurement parameters, and (3) they are reproducible.

Accordingly, this paper examines the effect of frequency and windowing on the measurement of TBOAE I/O functions. These measurements have two aims: to allow param-

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[a] Electronic mail: mepstein@ece.neu.edu

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eters to be chosen that provide reliable estimates of the I/O function and to determine the extent to which the form of the I/O function is dependent on measurement parameters. In addition, the effect of response delinearization on TBOAE I/O functions was examined to determine whether it would help isolate the nonlinear cochlear reflections.

II. METHOD

A. Procedure

In order to identify a frequency region near 1 kHz that produces strong otoacoustic emissions, the entire basilar membrane was stimulated by clicks. Frequencies near 1 kHz were selected because TBOAEs tend to be strong in this frequency region.

The OAEs were determined from the real, positive part of the cross spectrum (determined using MATLAB) of two independent averages of the time- windowed responses measured in the ear canal in order to help eliminate as much noise as possible. This method is based on the assumption that the OAE is phase locked to the stimulus and has highly repeatable components with identical phases in the two buffers in the time domain, and with zero phase in the cross spectrum. Thus, the emissions will be real and positive. As the phase of the measured responses becomes more variable, the phase in the cross spectrum is increasingly likely to differ from zero. Averaging and using only the real, positive part of the cross spectrum reduces the level of the recording that is not phase locked to the signal. The two averages used to get the cross spectrum were obtained by alternatingly entering the results of recordings into two different buffers. Subjects were presented with 200 clicks and responses were recorded at a sample rate of 50 kHz for 81.92 ms (4096 samples), including the time of the click itself. These recordings were windowed using a 21.48-ms (1024 samples) Hanning window covering the first portion of the recorded signal. Because the stimulus was a click, the direct stimulus was effectively eliminated by the very small value of the windowing function during the signal. The cross spectrum of the two sets of recordings was examined visually. The strongest peak around 1 kHz was chosen for further examination. To ensure that the peak was stable, this measurement was performed three times and peaks were used only if they appeared clearly in all three measurements. Once chosen, detailed measurements of tone-burst otoacoustic emissions at and around this frequency were performed.

Tone-burst evoked emissions were measured by presenting a series of brief tone bursts and recording the sound in the ear canal for 81.92 ms at a sample rate of 50 kHz. To allow calculation of the cross spectrum, the recordings were stored for further analysis in two interleaved sets over 360 trials. The stored responses were Hanning windowed using a 1024-sample window (21.48 ms). The window started after a delay between 13 and 20 ms in the first part of the experiment. A fixed value was chosen on the basis of those results and used thereafter. The spectrum of the windowed ear-canal response was band-pass filtered between 400 and 1400 Hz.

To reduce the effect of external noise, a response to a tone burst would be included in the average only if the noise floor was estimated to be less than 10 dB SPL. The noise floor for the rejection decision was calculated using a 21.48-ms Hanning windowing (with a window delay of 13 ms) of the difference between two samples. The noise intensity was then calculated as the sum of the squared magnitudes of the real FFT components between 32 and 819 Hz. This measure is highly conservative and guarantees that any data points above the noise are presented with a high level of confidence. Some of the measurements below the noise floor are also likely to be reliable, but the level of confidence is lower. Measurements were made for levels ranging in 5-dB steps from approximately 10 dB below the minimum level (typically 15–30 dB SPL) that produced an emission whose level exceeded the background noise to the maximum obtainable level. These measurements were repeated three times for each condition and averaged. Tests were performed at five frequencies to examine the extent to which the OAE measurements depend on local variations in response.

One final procedural variable to be examined is delinearization. Delinearization eliminates any response that is linearly related to the stimulus such as reflections from areas outside the cochlea (e.g., ear canal and ossicles). Their elimination would enhance the targeted TBOAE. The responses to the delinearized trials were recorded in two separate interleaved sets for 120 measurements per level (60 per set). If the system were completely linear, the two sets of responses would cancel out and nothing would remain except random noise. Delinearization was performed by subtracting the response to tone bursts with three times the normal amplitude from that obtained from the sum of three times as many presentations of tone bursts at the normal amplitude.

B. Stimuli

The clicks were 70-dB SPL 0.1-ms stimuli that contained energy between 450 Hz and 8 kHz. For each subject, a dominant peak in the click-evoked otoacoustic emissions (COAE) spectra between 850 and 1150 Hz was identified. This frequency and four additional test frequencies around this peak (-0.5, -0.25, $+0.25$, and $+0.5$ Barks$+$COAE peak) were selected. At each frequency, the tone burst presented had an equivalent rectangular duration of 6/frequency. These tone bursts had a Gaussian envelope to help contain the spectral spread of the signal due to onset and offset. The duration was chosen to obtain a useful compromise between frequency specificity and the ease of separating the stimulus from the emission that results from its presence. Using a long-duration signal makes the OAE difficult to measure because the signal would overlap the emission. Using a short-duration signal decreases frequency specificity because as the duration of the signal decreases, the bandwidth of the signal increases. Finally, during the delinearization trials, a tone with tripled amplitude was presented as every fourth stimulus.

C. Apparatus

Each subject was tested in a sound-attenuating booth. A PC-compatible computer with a signal processor (TDT AP2) generated the stimuli, and recorded responses. A TDT DA1

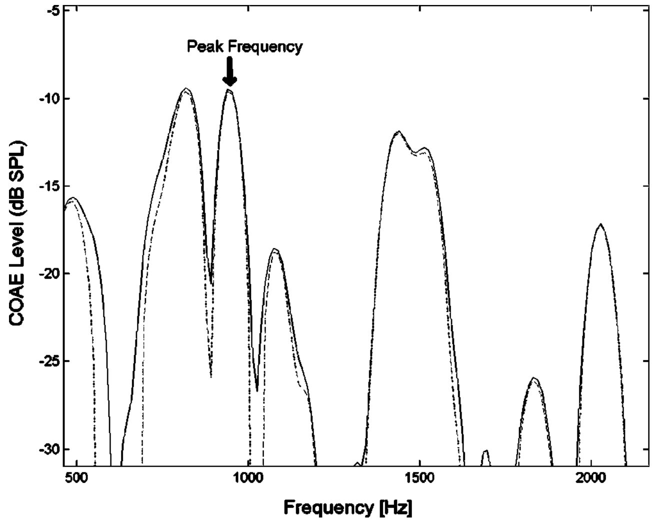

FIG. 1. Response to click stimuli for S1. The frequency in Hz is shown on the abscissa and the level of the resulting otoacoustic emission is on the ordinate. The peak frequency here that is closest to 1 kHz is 935 Hz. The solid lines show a single average measurement. The dotted lines show the positive, real part of the cross spectrum of two measurements.

converted the waveform calculated by the AP2 to an analog signal. The level of the stimuli was adjusted using a TDT PA4 attenuator and the signal was anti-alias filtered using a TDT FT5. The resulting signal was sent to a TDT HB6 headphone buffer and presented to the subject using an Etymotic Research ER-10C system, which also contained a microphone to record OAEs. The recordings from the ER-10C were anti-alias filtered, amplified, and converted to a digital signal using a TDT AD1. The digital signal was sent back to the AP2, which averaged the responses to the stimuli as explained previously and wrote the averaged signals to disk for further analysis.

D. Subjects

Six subjects (two male and four female) were tested monaurally. No subjects had a history of hearing difficulties or middle-ear pathology. Their audiometric thresholds did not exceed 10 dB HL for octave frequencies from 250 Hz to 4 kHz or 20 dB HL at 8 kHz (ANSI, 1989). Their ages ranged from 18 to 28 years.

III. RESULTS AND PRELIMINARY DISCUSSION

A. COAE measurement

Figure 1 is an example of the spectra obtained with the click stimuli for subject S1. The dotted line shows the cross spectrum between two different measurement sets. The solid line shows a single measurement set. Any real OAE should reveal a close correspondence between the two spectra. For this subject, the peak selected was at 935 Hz, and this frequency was used for further exploration with tone-burst stimuli. Similar analyses were made for the other five subjects to determine each one's dominant peak around 1 kHz.

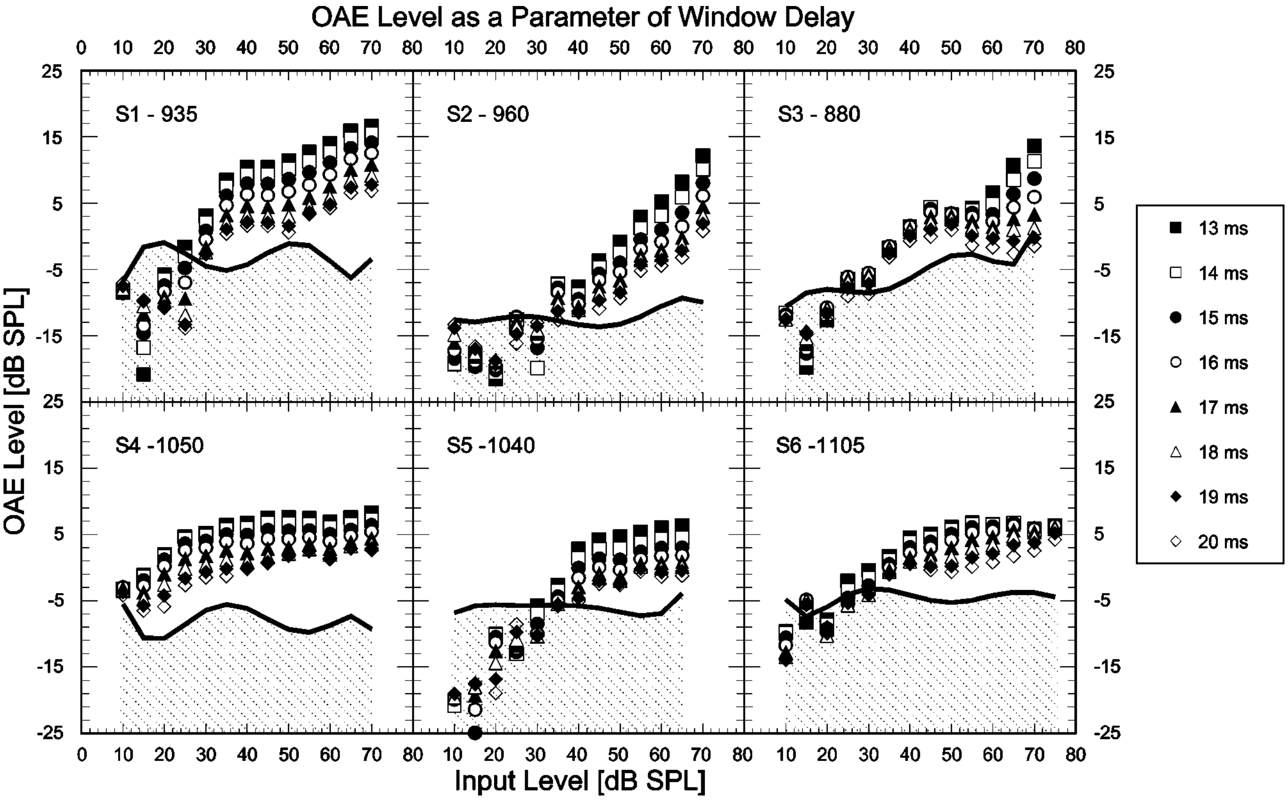

FIG. 2. The OAE level as a function of input level. Each panel is for a different subject. The OAEs were evoked by tone bursts and measured within a 21.48-ms window beginning 13 to 20 ms after the onset of the tone burst. Window delay is the parameter. Each delay is shown by a different symbol as indicated in the legend. The solid line is a polynomial fit to the background noise level.

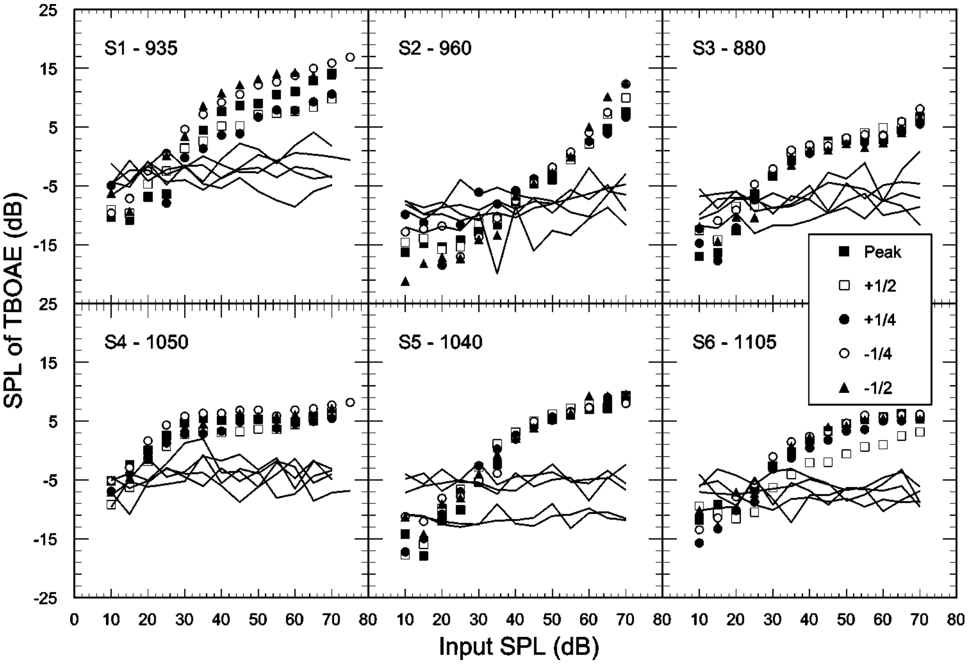

FIG. 3. The OAE level as a function of input level. The parameter is frequency offset in Barks. The noise floors are shown for comparison with Fig. 4. The average standard error of the mean emissions level above the noise floor is 0.77 dB with a range of levels from 0.15 to 1.47 dB. Peak frequency for each subject is given next to the subject label.

B. Effect of window delay

Figure 2 shows the results of varying the delay of the analysis window. Individual functions are shown for each window delay and the average noise floor is shown as a solid line.

Data that fall under the noise floor (i.e., within the shaded region) are considered questionable in terms of measurement accuracy and reliability. The curves all show a steeply increasing region followed by a flatter, compressive region. The TBOAE level decreases systematically as the delay increases, but the shape of the function hardly changes. The low-level slope is nearly linear for the delays examined. At moderate levels, a highly compressive I/O function is exhibited. There is also a slight increase in slope at higher levels. Similar results were obtained for most subjects, but some did exhibit a change in slope across the range of delays. Subject S3 showed an increase in slope above 55 dB SPL for delays of up to 16 ms, but the high-level slope decreased for 17- to 20-ms delays. The high-level function for subject S6 also changed shape across different window delays. The differences increased around 55–60 dB SPL. At 75 dB SPL, the highest level tested, the window delay seemed to have virtually no effect on the OAE level. This is likely to be due to the rapid decay of an OAE. For these two subjects, pushing the window too far back in time would cause a change in the resulting measurements. Therefore, it is important for the window to have a short or moderate delay. The location of the knee point of the function appears relatively invariant across all window delays for all subjects.

If the shape of the function depended markedly on the window delay, it would be difficult to decide which delay, if any, would show the ‘‘true’’ TBOAE I/O function. Overall, it was important to carefully select a time window that would not miss rapidly decaying OAEs, but would still avoid confusing the trivial reflections from the stimulus with an OAE. Therefore, a 15-ms window delay was used for all remaining measurements. A 15-ms delay seems to work well for all subjects, even those who exhibit rapidly decaying OAEs.

C. Effects of measurement frequency and delinearization

Figures 3 and 4 show six subjects’ TBOAE responses at five frequencies at and around the spectral peak in the COAE response, with and without delinearization, respectively. All subjects’ functions, except those of S2, exhibit a kneepoint close to 35 dB SPL. The functions exhibit similar slopes and compression, averaging about 0.23 above the kneepoint. Below the kneepoint, the functions are far less compressive. However, the delinearized functions in Fig. 4 are much closer to the noise floor than those in Fig. 3, surpassing the noise floor only when the input level reaches 35 or 40 dB SPL. In large part, this result may reflect that the I/O function is closer to being linear below the kneepoint, and that delinearization tends to cancel out any linear components of the response.

All subjects, except possibly S2, show some compressive portion of the I/O function. The compressiveness and the kneepoint varied from subject to subject, but were largely consistent across measurement frequency and delinearization conditions.

D. Summary of results

Generally, the delinearization produced poorer results with reduced magnitude of OAEs and a noise floor that was close to the OAE level. However, the delinearized functions tended to show compression slopes like those obtained without delinearization and virtually identical kneepoints as long as the relatively elevated noise floor in the delinearized responses did not obscure the kneepoint. The average delinearized slope was nearly equal to the slope obtained without delinearization in all cases.

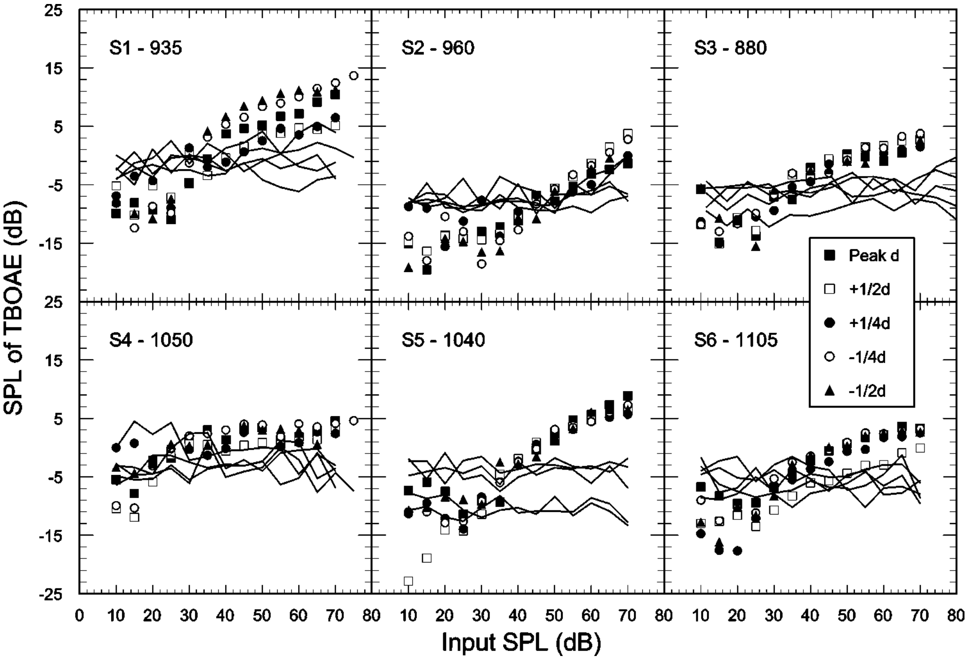

FIG. 4. The OAE level as a function of input level with delinearization. The parameter is frequency offset in Barks. The noise floors are also shown in order to illustrate the difference between the delinearized and normal functions (see Fig. 3). The standard error of the mean emission levels is 0.92 dB; they range from 0.02 to 3.08 dB. Peak frequency for each subject is given next to the subject label.

Table I shows the slope of the compressive upper part of the TBOAE I/O function and the kneepoint of the function for 13- to 20-ms window delays at the COAE peak frequency. Table Ia shows the correlation coeffecient r^2 for the fits to the functions fit to the windowing data. Tables II and III shows a summary of the slopes and kneepoints at the five selected frequencies with and without delinearization, respectively. Tables IIa and IIIa show the correlation coeffecient r^2 for the fits to the functions for which the slopes are displayed in Tables II and III. Functions were fit using a simultaneous square-error minimization of two line fits, one above and one below the variable kneepoint. The fits were done using the data from 20 to 65 dB SPL to help avoid points very far below the noise floor and points at the upper end of the function where the slope might be changing rapidly. With a few exceptions, most notably subject S2, the

TABLE I. (a) Line-fit slopes of upper parts of the OAE functions (beyond the kneepoint) at peak frequency for window delays of 13 to 20 ms. (b) r^2 correlation coefficients for line-fit slopes of OAE functions from 20 to 65 dB SPL at peak frequency for window delays of 13 to 20 ms.

(a)

Window Delay	13	14	15	16	17	18	19	20	Mean
S1 Slope	0.23	0.23	0.23	0.23	0.23	0.22	0.21	0.20	0.22
S2 Slope	0.75	0.57	0.49	0.44	0.42	0.38	0.40	0.45	0.49
S3 Slope	0.39	0.28	0.18	0.08	0.00	−0.07	−0.09	−0.13	0.08
S4 Slope	0.05	0.03	0.03	0.05	0.06	0.08	0.10	0.12	0.06
S5 Slope	0.12	0.11	0.12	0.13	0.13	0.13	0.12	0.09	0.12
S6 Slope	0.16	0.15	0.15	0.17	0.17	0.14	0.14	0.11	0.15
Mean Slope	**0.28**	**0.23**	**0.20**	**0.18**	**0.17**	**0.15**	**0.14**	**0.14**	**0.19**
S1 Kneepoint	35.41	35.37	35.24	35.01	35.00	35.00	35.00	35.00	35.13
S2 Kneepoint	30.00	35.00	35.00	34.93	29.86	41.87	43.86	47.67	37.28
S3 Kneepoint	38.08	39.84	40.79	41.19	41.85	42.36	41.91	41.35	40.92
S4 Kneepoint	27.12	31.98	31.21	22.46	22.20	22.37	22.83	24.02	25.52
S5 Kneepoint	41.49	41.13	40.72	40.48	40.88	41.78	42.01	41.77	41.28
S6 Kneepoint	37.72	38.59	38.99	38.36	37.13	36.16	34.25	35.00	37.03
Mean Kneepoint	**34.97**	**36.99**	**36.99**	**35.40**	**34.49**	**36.59**	**36.64**	**37.47**	**36.19**

(b)

r^2 Window delay	13	14	15	16	17	18	19	20	Mean
S1	0.996	0.994	0.989	0.978	0.958	0.928	0.907	0.892	0.955
S2	0.858	0.907	0.923	0.927	0.965	0.978	0.986	0.976	0.940
S3	0.963	0.962	0.964	0.982	0.991	0.996	0.991	0.982	0.979
S4	0.934	0.931	0.923	0.930	0.945	0.956	0.960	0.951	0.941
S5	0.998	0.999	0.999	0.996	0.992	0.988	0.951	0.889	0.976
S6	0.978	0.988	0.993	0.995	0.994	0.990	0.974	0.954	0.983
Mean	**0.955**	**0.963**	**0.965**	**0.968**	**0.974**	**0.973**	**0.961**	**0.941**	**0.962**

TABLE II. (a) Line-fit slopes to the upper part of the function for an average of three TBOAE measurements for five frequencies without delinearization. The frequencies are expressed in the chart by their distance from the peak frequency in Barks. (b) r^2 correlation coefficients for line-fit slopes of an average of three TBOAE measurements for five frequencies *without* delinearization from 20 to 65 dB SPL.

(a)

	Frequency (Barks)					
	Peak	$+\frac{1}{2}$	$+\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	Mean
S1 Slope	0.22	0.18	0.23	0.24	0.10	0.19
S2 Slope	0.52	0.55	0.37	0.65	0.71	0.56
S3 Slope	0.14	0.18	0.16	0.17	0.17	0.16
S4 Slope	0.02	0.07	0.03	0.04	0.04	0.04
S5 Slope	0.25	0.21	0.20	0.27	0.29	0.24
S6 Slope	0.14	0.19	0.18	0.14	0.11	0.15
Mean Slope	**0.21**	**0.23**	**0.20**	**0.25**	**0.24**	**0.23**
S1 Kneepoint	37.86	33.73	37.58	34.77	37.63	36.32
S2 Kneepoint	35.35	35.47	34.99	35.82	34.14	35.15
S3 Kneepoint	36.28	34.96	35.35	33.49	35.77	35.17
S4 Kneepoint	26.52	27.29	29.06	25.06	28.68	27.32
S5 Kneepoint	38.36	36.87	36.88	37.74	36.35	37.24
S6 Kneepoint	37.11	30.42	35.44	33.39	36.08	34.49
Mean Kneepoint	**35.25**	**33.12**	**34.88**	**33.38**	**34.78**	**34.28**

(b)

	Frequency (Barks) r^2					
	Peak	$+\frac{1}{2}$	$+\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	Mean
S1	0.978	0.983	0.954	0.996	0.989	0.980
S2	0.991	0.985	0.931	0.956	0.982	0.969
S3	0.977	0.976	0.992	0.980	0.949	0.975
S4	0.918	0.923	0.748	0.877	0.932	0.880
S5	0.980	0.995	0.995	0.942	0.984	0.979
S6	0.990	0.987	0.983	0.984	0.958	0.980
Mean	**0.972**	**0.975**	**0.934**	**0.956**	**0.966**	**0.960**

slopes are quite similar across frequency and delinearization conditions.

If window delay has no effect, then all the values in a single row in Table I should be identical. Although some variations were present for some subjects at the lowest and highest window delays, only S3 showed large changes in slope for moderate values of window delay. An ANOVA on the effect of window delay indicated that there was a significant effect (P value <0.0001). However, Scheffe *post-hoc* analysis shows significant differences only exist between the longer and shorter windows (13/17, 13/18, 13/19, 13/20, 14/18, 14/19, 15/19, 15/20, and 16/20).

If frequency shifting and delinearization both have no effect, then all the values in a single row of Tables II and III should be identical. Again, some minor variation was seen in some subjects, but there was generally only a very small change in the slope resulting from small shifts in stimulus frequency and virtually no change was apparent when looking at average results. An ANOVA on the effect of frequency yielded a P value of 0.06, just greater than a result showing significance. Scheffe *post-hoc* analysis, however, showed that all frequency interactions yielded P values >0.3 except the interaction between $-\frac{1}{4}$ Bark and $+\frac{1}{2}$ Bark, which had a P value of 0.095, thereby reinforcing the assertion that there is no significant effect of small frequency changes on the amplitude of TBOAEs.

The slopes for subjects S5 and S6 appear to be larger with delinearization than without, but the mean slopes with and without delinearization were identical, indicating that delinearization does not have an effect on the shape of the upper portion of the TBOAE I/O function.

IV. GENERAL DISCUSSION

Although the change in slope caused by delinearization was small for most subjects, there was a general tendency for delinearization to reduce the levels of the OAEs near the kneepoint more than those at high levels. A small increase in slope occurred because of this low-level reduction. However, at the higher levels (approximately 65–80 dB SPL), the slope with and without delinearization was nearly identical in all cases. Overall, there was no benefit to using delinearization. In fact, it reduced the level of the signal both in absolute terms and, more importantly, relative to the noise floor. Thus, it made measurements more time consuming and more uncertain for low stimulus levels. To the extent that it is important to characterize the nearly linear low-level part of the function, delinearization is likely to be undesirable because it eliminates any linear part of the response. Accordingly, delinearization is counterproductive for the present purpose because merely using a window delay sufficiently eliminates the trivial echo.

TABLE III. (a) Line-fit slopes to the upper part of the function for an average of three TBOAE measurements for five frequencies with delinearization. The frequencies are expressed in the chart by their distance from the peak frequency in Barks. (b) r^2 correlation coefficients for line-fit slopes of an average of three TBOAE measurements for five frequencies *with* delinearization from 20 to 65 dB SPL.

(a)

Frequency (Barks)
(with delinearization)

	Peak	$+\frac{1}{2}$	$+\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	Mean
S1/Slope	0.23	0.20	0.21	0.23	0.11	0.20
S2/Slope	0.30	0.47	0.26	0.51	0.45	0.40
S3/Slope	0.18	0.20	0.20	0.22	0.18	0.19
S4/Slope	0.03	0.04	0.03	0.02	−0.01	0.02
S5/Slope	0.46	0.35	0.32	0.37	0.34	0.37
S6/Slope	0.21	0.23	0.25	0.18	0.14	0.20
Mean Slope	**0.24**	**0.25**	**0.21**	**0.25**	**0.20**	**0.23**
S1/Kneepoint	40.20	30.02	29.94	38.07	41.77	36.00
S2/Kneepoint	35.03	35.54	34.47	35.77	35.33	35.23
S3/Kneepoint	37.46	35.65	35.84	34.63	36.25	35.97
S4/Kneepoint	28.18	27.89	30.03	29.82	31.10	29.41
S5/Kneepoint	36.01	37.16	37.11	36.58	34.50	36.27
S6/Kneepoint	35.77	38.75	30.44	38.07	44.60	37.52
Mean Kneepoint	**35.44**	**34.17**	**32.97**	**35.49**	**37.26**	**35.07**

(b)

Frequency (Barks) r^2 delinearized

	Peak	$+\frac{1}{2}$	$+\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{2}$	Mean
S1	0.965	0.835	0.748	0.966	0.982	0.899
S2	0.949	0.981	0.753	0.880	0.941	0.901
S3	0.885	0.931	0.947	0.981	0.854	0.920
S4	0.647	0.923	−0.069	0.846	−0.074	0.455
S5	0.903	0.959	0.956	0.973	0.919	0.942
S6	0.967	0.947	0.996	0.960	0.950	0.964
Mean	**0.886**	**0.929**	**0.722**	**0.934**	**0.762**	**0.847**

In considering using TBOAEs to characterize cochlear function, it is important that the measurement be robust, at least across a reasonable range of levels. If the form of the I/O function varied significantly with frequency, it would be impossible to know which measured function, if any, was the ‘‘correct’’ I/O function. Interestingly, the frequency at the peak of the COAE spectrum did not always produce the strongest TBOAE. For a given subject, the frequency that evoked the greatest response tended to be the same across all levels, but the relation of this frequency to the subject’s COAE peak was not consistent across subjects. This may be a result of multiple, strong OAE-producing locations present near each other on the basilar membrane, which apparently cause the ‘‘best’’ frequency to depend on whether the evolving stimulus has a broad or narrow spectrum. Regardless of the cause, the functions did not tend to cross one another. Although no particular distance from the COAE peak seemed better than any other (on average), the frequency at the peak of the COAE spectrum generally produced a moderate to large response within the group of five frequencies. The measurements at various frequencies around the peak of the COAE spectrum showed that the form of the TBOAE I/O function was not dependent on frequency, at least in the range examined. In other words, there was little or no interaction between the test frequency and TBOAE I/O shape and it is sufficient to test at one frequency.

V. SUMMARY

Through an examination of measurement paradigms and parameters, an effective technique for measuring tone-burst otoacoustic emissions with minimal noise has been developed. These measures are largely independent of specific choices of measurement parameters and make a good starting point for considering the use of TBOAEs to examine cochlear function. The effect of frequency and windowing on the measurement of TBOAE I/O functions was examined and, under the conditions used, tone-burst OAEs can be measured without concern for these potential confounds as long as a moderate, sensible time-window delay is used. In practice, time windowing is a simple and effective way of eliminating almost all of the response to the signal itself, obviating the need for delinearization techniques, which tend to add noise and complexity to the measurements without providing any clear beneficial change to the results. In fact, delinearization tended to diminish the quality of the data, especially at low levels. In addition, small changes in frequency did not affect the shape, kneepoint, or slope of the I/O function, indicating that the exact test frequency selected for an individual is not critical. Thus, it is likely that any TBOAE measurements may be a useful tool for examining cochlear function and procedural choices can be made on the bases of simple criteria, such as the OAE-to-noise-floor level difference and the lowest level at which TBOAE can be observed.

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