BASILAR-MEMBRANE ACTIVITY AND LOUDNESS

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Abstract

Buus and Florentine (ISP meeting 2001) presented evidence that basilar-membrane velocity growth functions are proportional to the square root of loudness functions derived from temporal and spectral integration. Although it is not possible to directly measure basilar-membrane activity in humans, it is likely that tone-burst otoacoustic emission input-output functions, at least at low and moderate levels, are closely related to the amount of basilar-membrane activity. To further examine this relation, tone-burst otoacoustic emissions are compared with loudness functions derived from a combination of data from temporal integration of loudness and spectral loudness summation, as well as loudness functions that are more directly measured using cross-modality matching. Tone-burst otoacoustic emission input-output functions show a strong correspondence to loudness measured using all these methods. These findings support the idea that loudness is closely related to basilar-membrane activity and that tone-burst otoacoustic emissions may provide rapid, non-invasive insight into cochlear activity.

A non-invasive method for understanding basilar-membrane activity in humans would be invaluable for understanding how the active portion of the cochlea functions. At the 2001 ISP meeting, Buus and Florentine presented evidence that human loudness growth is proportional to the square of basilar-membrane velocity measured in chinchillas (Ruggero *et al.*, 1997). Withnell and Yates (1998) first suggested that otoacoustic emissions might be a suitable tool for examining basilar-membrane nonlinearity. Epstein and Florentine (2005(1)) confirmed that loudness measured using temporal and spectral summation is proportional to tone-burst otoacoustic emissions (TBOAEs). However, these experiments rely on loudness models and do not directly assess loudness. Therefore, a follow-up experiment in which loudness is assessed using a cross-modality matching procedure is presently compared with TBOAEs.

Method

Otoacoustic emissions were recorded using an Etymotic ER-10C system. The stimuli were 6-cycle, Gaussian-windowed tone bursts at a frequency close to 1000 Hz. The responses were recorded by a computer and time-windowed using a 20-ms Hanning window delayed by 15-ms from the beginning of the presentation. Three repetitions of two interleaved sets of TBOAEs totaling 360 presentations were recorded for the comparison with temporal and spectral summation and one repetition of two sets totaling 600 trials was recorded for the comparison with cross-modality matches. The recordings were bandpass filtered between 400 and 1400 Hz. The real, positive part of the cross spectrum between the two sets was used to determine the final TBOAE value. [See Epstein *et al.* (2004) for a detailed description of the task.]

Cross-modality matches between loudness and string length were made by asking listeners to cut a piece of string "as long as a sound was loud." The final match for each level was the geometric mean of six matches performed over the course of two sessions with three repetitions per session. [See Epstein and Florentine (2005(2)) for a detailed description of the task.]

Temporal integration of loudness was measured using an adaptive procedure in which a listener's point of subjective loudness equality for long and short tones was determined. Loudness was derived from temporal integration data using a model (Buus, 1999) that assumes that the ratio between loudnesses for long and short tones is independent of level; this is known as the Equal-Loudness-Ratio Hypothesis (Epstein and Florentine, 2005; Florentine *et al*., 1996). [See Florentine *et al*. (1996; 1998) for a detailed description of the task used for measuring temporal integration of loudness.]

Spectral summation of loudness was measured using an adaptive procedure in which a listener's point of subjective loudness equality for pure tones and multitone complexes was determined. This technique allows the assessment of loudness at low levels (Buus *et al.*, 1998) by assuming that the loudness of a four-tone complex with equally loud components will have four times the loudness of any one component (Fletcher and Steinberg, 1924; Fletcher and Munson, 1933). This assumption also allows the loudness function to be modeled by examining the relationship between the loudness of pure tones and tone complexes at different levels to determine the rate of loudness growth. [See Buus *et al.* (1998) for a detailed description of the task used for measuring spectral summation and the model used to derive loudness.]

Listeners

Six normal-hearing listeners participated in each of the comparisons between TBOAEs and spectral and temporal summation. Two normal-hearing listeners participated in the comparison between TBOAEs and cross-modality matches.

Results and Discussion

For all results, data obtained using the different techniques were normalized so that they could be directly compared. Loudness derived using spectral summation and temporal integration is dimensionless and is plotted on a log scale in terms of number of logarithmic units. Tone-burst otoacoustic emissions were normalized to number of logarithmic units by dividing the level of the emission by 10. Additionally, because the alignment of these units is arbitrary, one free parameter was allowed to ensure proper vertical alignment on the plots.

In the case of the cross-modality matches, the loudness functions derived using this technique were abnormally shallow (Epstein and Florentine, 2005), but were shown to be quite close to the expected slope when squared. Therefore, for comparison between this technique and TBOAEs, the cross-modality matches were squared.

Figure 1 shows a comparison of a loudness function derived from spectral loudness summation and tone-burst otoacoustic emissions.

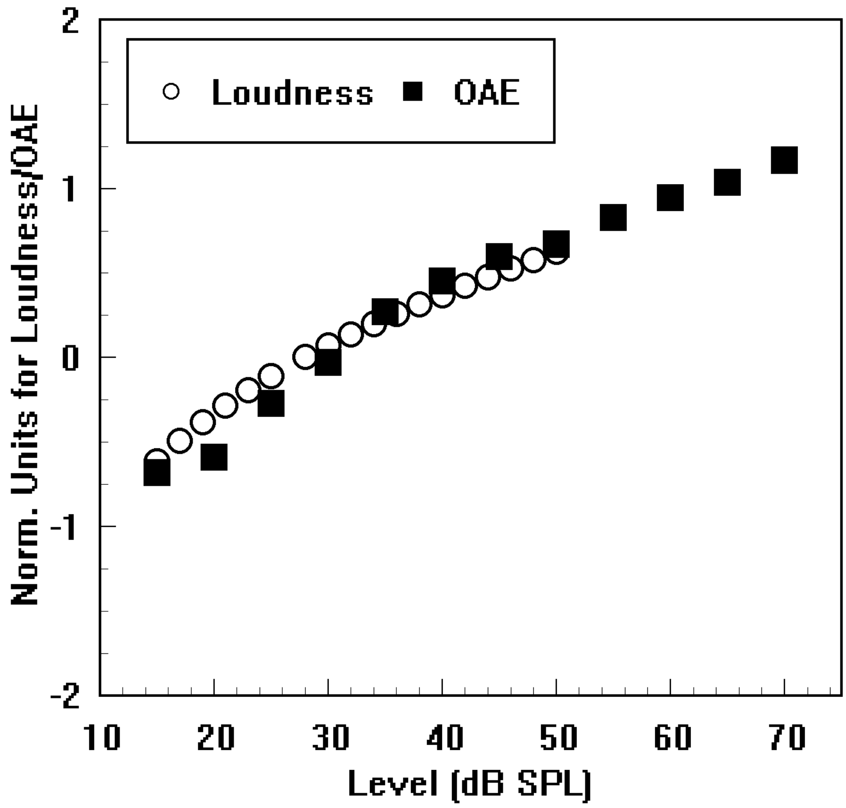

Figure 1. A mean comparison between loudness derived from spectral loudness summation (open circles) and tone-burst otoacoustic emissions (filled squares) for six normal-hearing listeners. Loudness and otoacoustic emissions are presented in normalized units in order to directly allow comparison between the two measurements.

The shapes of these two functions are quite similar. In general, these techniques correspond well across the whole range of levels tested. There is some variability seen at low levels in the coherence of the TBOAE function. Emissions measured at low levels are in competition with background noise and variability of low-level measurements, though relatively small, is much greater than for similar measurements made at high levels. This variability likely explains the small discrepancy seen between the two functions between 20 and 35 dB SPL. Overall, however, the similarity of these two functions indicates that it is likely that each technique is providing insight into the same physiological and perceptual phenomenon. Unfortunately, it is not possible to perform loudness summation at levels above 45 dB SPL without the assumptions breaking down. The primary issue is that multitone complexes result in partial inter-component masking when the levels of the components are sufficient, but will not result in masking at lower levels (Zwicker, 1958). This masking does not seem to occur at lower levels. Additionally, loudness may grow slightly differently at higher levels due to threshold microstructure (Mauermann *et al.*, 2004).

Figure 2 shows a comparison of a loudness function derived from measures of temporal integration of loudness and tone-burst otoacoustic emissions.

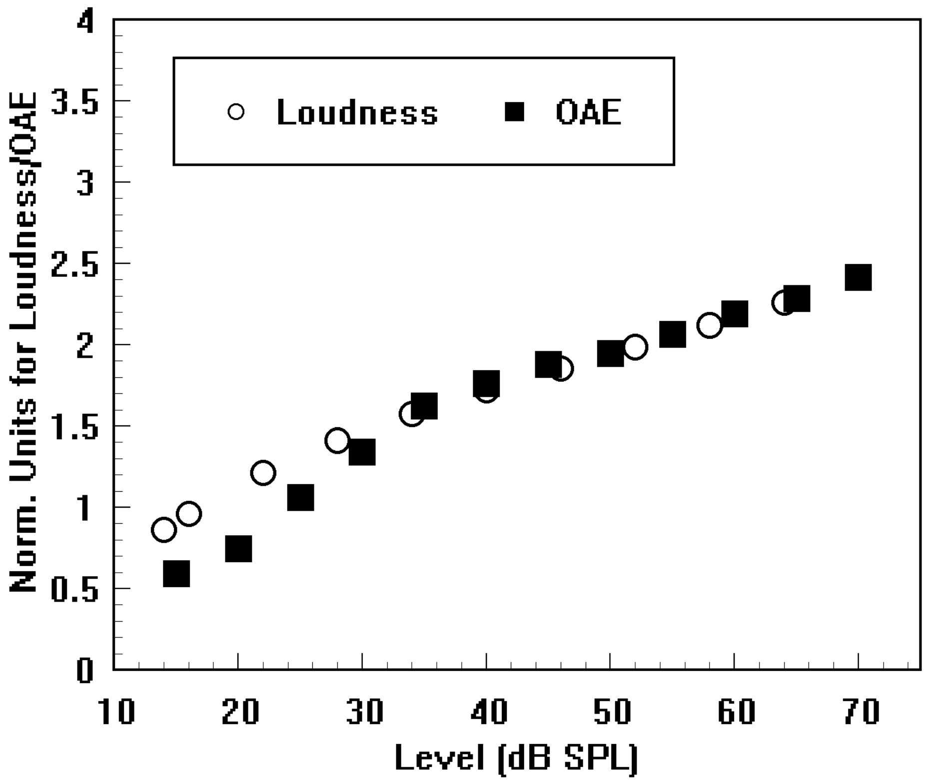

Figure 2. A mean comparison between loudness derived from temporal integration (open circles) and tone-burst otoacoustic emissions (filled squares) for six normal-hearing listeners. Loudness and otoacoustic emissions are presented in normalized units in order to directly allow comparison between the two measurements.

These two functions match extremely well above 30 dB SPL. There is a noteworthy discrepancy at low levels. This is not terribly surprising as the technique used for deriving this loudness function assumes that the Equal-Loudness-Ratio Hypothesis, which states that the ratio between the loudnesses of long and short tones is independent of level, is true for all levels. Epstein and Florentine (2005) found that this hypothesis is not completely true below 40 dB SPL. Because of this finding, it is expected that this loudness model will overestimate loudness below 40 dB SPL.

It is clear from Figure 2 that the match between TBOAEs and loudness derived from temporal integration of loudness fails only below 40 dB SPL. Again, the similarity of these two functions indicates that it is likely that each technique is providing insight into the same physiological and perceptual phenomenon.

Figure 3 shows a comparison of loudness assessed using a cross-modality matching technique and tone-burst otoacoustic emissions for two listeners. Each plot shows the results from one individual. [Note: the variability for individuals is greater than the mean variability seen in the earlier figures.]

The comparison of TBOAEs and cross-modality matches shows a clear and distinctive similarity between the two measures. Although only two listeners are presented here, their results differ enough to see that slight differences in the slope and shape of the function are highly evident and coherent in both measures. Cross-modality matching is the only technique used here that directly assesses loudness, rather than modeling it. Therefore, the correspondence of this measure with TBOAEs provides strong support that, if loudness is

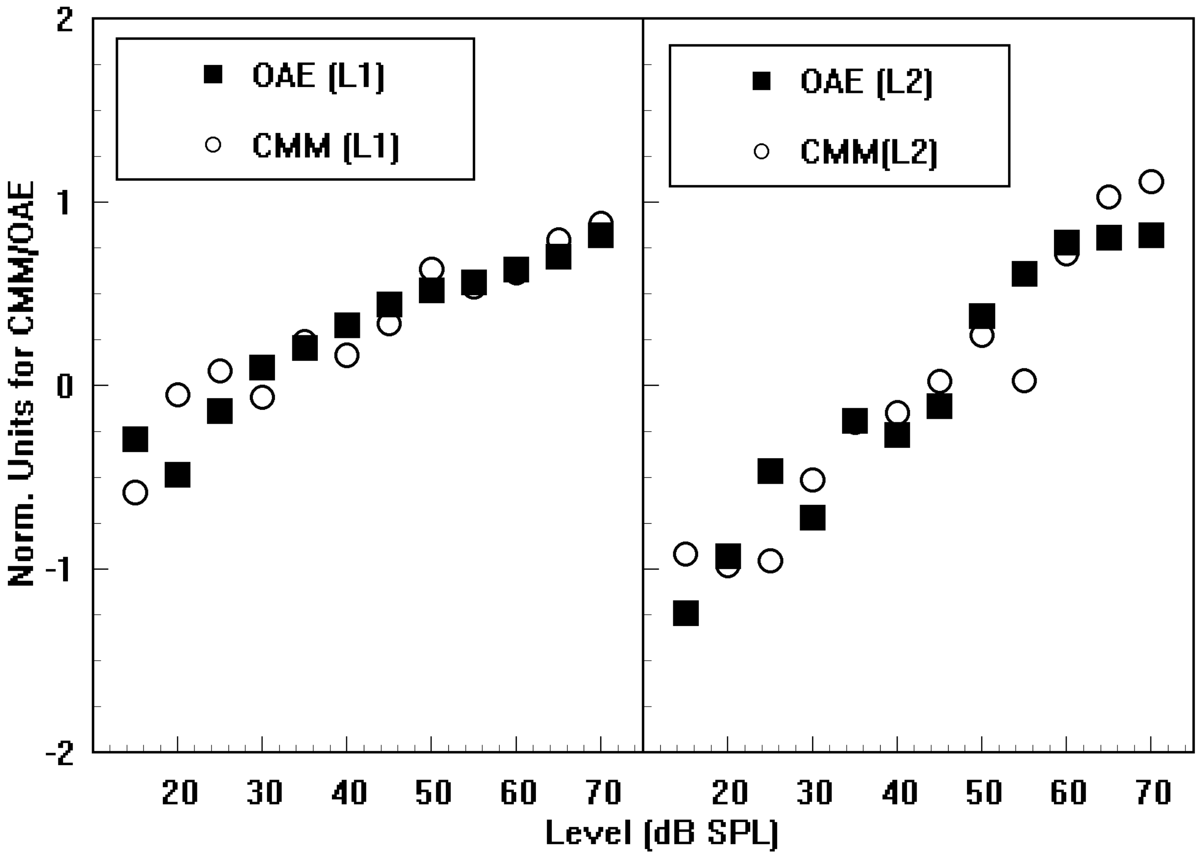

Figure 3. A comparison between the square of cross-modality matches (open circles) and tone-burst otoacoustic emissions (filled squares) for two normal-hearing listeners. Cross-modality matches are presented as the logarithm of string length squared and otoacoustic emissions are presented in normalized units in order to directly allow comparison between the two measurements.

related proportionally to basilar-membrane activity, then TBOAEs are also likely to be related.

Summary

Prior evidence had indicated that both loudness and otoacoustic emissions might be closely related to basilar-membrane activity. Therefore, three measures of loudness were compared with tone-burst otoacoustic emissions to see whether the two different techniques, one a physiological phenomenon, the other a psychoacoustical phenomenon, showed close correspondence to one another. Although the three techniques for measuring and modeling loudness have known weaknesses in particular scenarios, the combination of the three showed strong support for the idea that both loudness and otoacoustic emissions are related to basilar-membrane activity and, therefore, each other.

Acknowledgments

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