Reply to "Comment on 'Enhancement of the transient-evoked otoacoustic emission produced by the addition of a pure tone in the guinea pig'" [J. Acoust. Soc. Am. 105, 919–921 (1999)]

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In a recent paper Withnell and Yates [J. Acoust. Soc. Am. **104**, 344–399 (1998)] suggested that the TEOAE might be comprised of significant quantities of intermodulation distortion energy, based on a series of suppression experiments involving the measurement of the TEOAE with the addition of a pure tone. Ren and Nuttall [J. Acoust. Soc. Am. **105**, 919–921 (1999)] have suggested an alternative explanation for our experiments, wherein a pure tone produces a local impedance change in the nonlinear mechanical properties of the basilar membrane: emission energy at frequencies below the frequency of the pure tone is suggested to arise from reflections at this impedance discontinuity. In this Letter, a response to their hypothesis is given, arguing that it is not consistent with experimental findings, and that, in fact, the TEOAE is comprised predominantly of intermodulation distortion energy [Yates and Withnell, Assoc. Res. Otolaryngol. Abstr. **21**, 5 (1998)]. © *1999 Acoustical Society of America.* [S0001-4966(99)04102-8]

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We thank Dr. Ren and Dr. Nuttall for their letter offering an alternative interpretation for the findings of Withnell and Yates (1998), although we do observe at the outset that we had already considered and rejected a similar explanation in that paper.

The most important finding of Withnell and Yates (1998) was the absence of strong, frequency-specific suppression of the transient-evoked otoacoustic emission (TEOAE) by a simultaneously presented pure tone, as Sutton (1985) had found previously but Kemp and Chum (1980) had not. The mixture of enhancement and suppression of the TEOAE at frequencies quite unrelated to the tone was an unexpected and entirely secondary finding. To explain our results, we proposed that the TEOAE might be composed of significant quantities of intermodulation distortion energy, generated by interactions between the spectral components of the stimulus click at a continuum of places along the cochlea. In such a proposal, the addition of a pure tone would reduce the click-evoked basilar membrane vibration at, and basal of, the characteristic place of the tone, thereby reducing the amount of intermodulation energy produced at that place. Significant quantities of intermodulation distortion energy would still be generated by activity at other, more apical sites on the basilar membrane, and the result at any given response frequency would depend upon the precise phase relationship between the suppressed and unsuppressed energy. Such a proposal, it was noted, provided a satisfactory explanation for the results of Avan *et al.* (1993, 1995, 1997), findings which were discordant with an independent generator hypothesis (Kemp, 1986; Probst *et al.*, 1986; Prieve *et al.*, 1996). Indeed, it was Prieve *et al.* (1996)

who recognized that an independent generator hypothesis for the TEOAE was inconsistent with the level-dependent nonlinear nature of the cochlea.

Ren and Nuttall (1999) have offered an alternative explanation for our findings: namely that the addition of a pure tone produces a local impedance change in the nonlinear mechanical properties of the basilar membrane. Traveling waves at frequencies below the pure-tone frequency encounter the impedance discontinuity and are reflected from the CF location of the pure tone rather than their own CF locations (Ren and Nuttall, 1999). This purportedly provides a mechanism for the observed enhancement of the TEOAE at frequencies below the tone frequency. There is no evidence in the literature, however, of reflections of traveling waves of low frequency caused by simultaneous presentation of higher frequency tones, and such an alternative explanation does not explain the fact that no suppression of the TEOAE was routinely observed at the frequency of the pure tone. Ren and Nuttall argue that suppression of the TEOAE might not be a necessary concomitant of basilar membrane suppression because under their model the component of the wave reflected from the tone CF place may be greater than that from the emission CF place, leading to either enhancement or suppression. However, in the case of suppression of the TEOAE that we were looking for, the characteristic place of the suppressor and of the response frequencies we expected to suppress were one and the same place. It is therefore immaterial which reflection dominates: if the amplitude of the click-induced basilar membrane vibration were reduced, then the TEOAE must necessarily also be reduced.

A readily examinable consequence of the Ren and Nuttall model is that if energy at frequencies below that of the pure tone is reflected from the impedance discontinuity created by the tone (so dominating the total reflected energy at those frequencies), then the group delay of such energy will
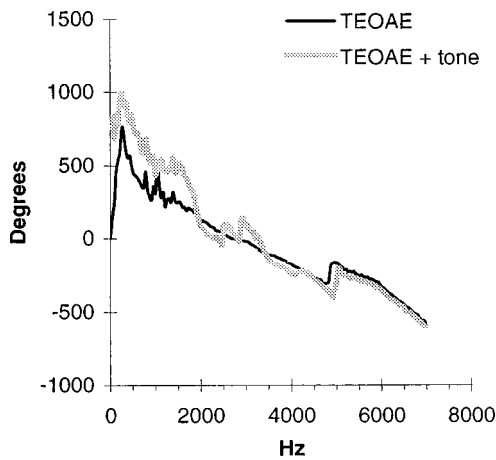
FIG. 1. Phase response data for a TEOAE recorded in response to a 0- to 7-kHz click stimulus with and without the addition of a 5 kHz tone. Phase data below ~1500 Hz is noise.

be less than for the same energy without the pure tone present (which must propagate to its own characteristic place and then back again to the stapes). The difference in group delay will be most manifest at frequencies lower than the pure-tone frequency. Thus, while we hesitate to introduce new data in a communication of this kind, we feel obliged to provide an example of previously unpublished phase data from the suppression experiments of Withnell and Yates (1998). Phase data typically showed the group delay to remain unchanged at frequencies lower than that of the frequency of the added pure tone: Fig. 1 provides an example for the TEOAE in response to a 0- to 7-kHz click, with and without the addition of a 5-kHz pure tone [corresponds to Fig. 1 of Withnell and Yates (1998)]. In fact, Fig. 1 shows no change in the group delay of the TEOAE across the frequency range of the stimulus following the addition of the 5-kHz pure tone.

Ren and Nuttall concede that TEOAE energy outside of the stimulus passband (above 10 kHz) in Fig. 4 of Withnell and Yates (1998) is consistent with intermodulation distortion energy contributing to the TEOAE (Ren and Nuttall, 1999), but also observe that no energy is evident outside of the stimulus passband for Figs. 2 and 3. Closer inspection of Fig. 3 in fact reveals that, with the addition of a 6-, 9-, or 12-kHz tone, there is energy in the TEOAE outside the stimulus passband (0–5 kHz). However, Ren and Nuttall (1999) argue that since the single-tone burst evoked TEOAE also shows bandpass features rather than a single frequency peak on the spectrum (Yoshikawa et al., 1998), TEOAE energy outside the single-tone bandwidth is not evidence that the TEOAE is generated by the mechanism of the DP production, and so they suggest it can be concluded that TEOAE energy outside the stimulus passband may not be an indicator of DP production in the cochlea. However, the experiments of Yoshikawa et al. (1998), which they cite, were not carried out with pure tones but rather with cosine-modulated tones of 5-ms duration. Such stimuli have a −20-dB bandwidth of about 600 Hz, very close to, but slightly narrower than, the bandwidth of the responses reported. At center frequencies in the range 1–3 kHz, as used by Yoshikawa et al., there is ample opportunity for intermodulation to occur in a

~300-Hz band. Thus, the experiments of Yoshikawa et al. cannot be taken as evidence for production of other frequencies by a single frequency stimulus.

Ren and Nuttall's alternative explanation for the findings of our paper (Withnell and Yates, 1998) is based on their recently reported experiments (Ren and Nuttall, 1998). In this paper, they describe their findings for the electrically evoked otoacoustic emission (EEOAE), stimulated from an extra-cochlear electrode, with the addition of an acoustical pure tone. The present letter (Ren and Nuttall, 1999) claims that the EEOAE in Ren and Nuttall (1998) was enhanced below the pure-tone frequency and suppressed above, but inspection of their figures (Ren and Nuttall, 1998) shows that the response was predominantly one of suppression at all frequencies, apart from a band of enhancement about one-half octave wide and just below the tone frequency. As we commented in our original paper, our TEOAEs were enhanced and suppressed in a far less predictable manner by a pure tone. Ren and Nuttall (1999) draw their parallel between these EEOAE findings and our TEOAE findings based on a claimed similarity between clicks being wideband stimuli and the EEOAE being obtained in response to a constant current with swept frequency across a wide frequency range. However, in a nonlinear system, the sweeping of frequency, which is essentially the presentation of a single frequency at any one time, is not equivalent to a click which presents all frequencies simultaneously.

Ren and Nuttall's (1998) basic observations are in conflict with many reports of interactions between EEOAEs and tonal acoustical stimuli (e.g., Mountain and Hubbard, 1989; Xue et al., 1993; Nakajima et al., 1996, 1998; Kirk and Yates, 1996), all of which report only enhancement of EEOAE responses, except for the case of electrical frequencies close to or just above the local CF of the electrode site, regardless of the frequency of the tone. Ren and Nuttall's (1998) technique would appear to approximate an injection of electrical current into the basal region of the cochlea (the delay times of the EEOAEs would support this). They show some evidence of propagation of a traveling wave from the effective site of electrical stimulation, but not such direct evidence as has been described previously (Kirk and Yates, 1994), where it was demonstrated that acoustical tonebursts could forward-mask compound action potentials generated by the electrically evoked traveling waves, and that electrically evoked traveling waves could forward-mask acoustically generated compound action potentials.

There is no doubt that acoustical tones may modulate the amplitude of EEOAEs, but little direct evidence to indicate that they change intracochlear reflection patterns of traveling waves. Recently, Kirk and Yates (1998) showed that acoustically induced vibration of the basilar membrane directly modulates the EEOAE in direct proportion to the mean open probability of mechanical-to-electrical transduction channels of outer hair cells, and have also suggested that a small shift in outer hair cell operating point could explain acoustic enhancement. Alternatively, Mountain and Hubbard have, for some time, claimed that enhancement of the EEOAE is due to release of the basilar membrane vibrations from a negative feedback loop at low frequencies. No reso-

lution of these competing explanations is yet available, but there is considerably more direct evidence for both of these suggestions than for the reflection hypothesis of Ren and Nuttall (1999).

Finally, we reported in February of this year at the Midwinter Meeting of the Association for Research in Otolaryngology (Yates and Withnell, 1998) that intermodulation distortion energy does indeed contribute to the TEOAE. Our experiments using high-pass filtered clicks demonstrated the presence of physiological vulnerable energy, not present in the original stimulus, both above and below the stimulus passband. This provides unequivocal evidence that the TEOAE is comprised of intermodulation distortion energy; indeed, we were able to demonstrate in this report that the TEOAE is predominantly comprised of intermodulation distortion energy.

ACKNOWLEDGMENTS

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