

Two-Tone Suppression in Apical Cochlear Mechanics

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Mechanical responses to one- and two-tone stimuli were recorded from the cochlear partition in the third turn of the chinchilla cochlea. The most sensitive or 'best' frequencies (BFs) for the sites studied were ~600Hz. Two-tone suppression (2TS) of the responses to near BF probe tones was noted using suppressor tones either above or below the BF. Both the suppression thresholds (the suppressor levels causing a 10% reduction in the amplitudes of the probe-evoked responses) and the rates of growth of suppression with suppressor level varied systematically with the suppressor frequency. Below-BF suppressor tones reached suppression threshold when they evoked displacements which were comparable to those evoked by the probe tones alone (typically between ~10 and 30nm for 40–50dB SPL probe tones), whereas above-BF suppressor tones evoked much lower displacements at the site studied (between 10 × lower at ~800Hz and 100 × lower at ~2kHz). The rates of growth of suppression varied from ~30% per 10dB below 800Hz to ~10% per 10dB at ~3kHz. Low frequency (e.g., 100–200Hz) suppressor tones evoked a level-dependent mixture of phasic (ac) and tonic (dc) suppression. These findings are discussed in relation to previous studies, most of which were performed in the more basal turns of the cochlea.

Keywords: Cochlear mechanics, basilar membrane, tectorial membrane, two-tone suppression

THE MAMMALIAN COCHLEA is highly sensitive to acoustic stimuli. This sensitivity is brought about in part through the mechanics of the cochlear partition. The basilar membrane's (BM) responses to low levels of stimulation are subject to an amplification process which is highly dependent on the functional state of the organ of Corti. This amplification is often referred to as an 'active' process (for reviews see Patuzzi and Robertson, 1988; Dallos, 1992). At higher levels of

stimulation, the BM's responses are subject to less amplification, and the mechanical system becomes more 'passive' in nature.

The nonlinearities which accompany the transition from active to passive cochlear mechanics can lead to complex interactions in the responses to many acoustic stimuli. One such interaction is demonstrated in the phenomenon of two-tone suppression (2TS): the cochlea's response to one tone can be reduced quite substantially

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when a second tone is presented at the same time. Nonlinear interactions of this type are of potential importance in many areas of hearing research (e.g., in the peripheral encoding of speech stimuli—see Sachs and Young, 1980; and in determining the masking effects of background noise—see Rhode *et al.*, 1978).

Systematic studies of 2TS in the cochlear nerve (e.g., by Delgutte, 1990; Javel *et al.*, 1983; and Prijs, 1989) show that neural responses to two-tone stimuli vary with the inferred place of innervation in the cochlea. In particular, the rate of growth of 2TS with increasing levels of suppressor tone stimulation is an increasing function of increasing characteristic frequency (CF; see Figs. 7 and 9–13 of Delgutte, 1990), and the range of frequencies which elicit a given amount of 2TS (i.e., the logarithmically normalized widths of the 2TS tuning curves, particularly on the high frequency side of the CF) is a decreasing function of increasing CF (see Fig. 3 of Prijs, 1989). The basic aim of the present study is to determine whether these variations have their origins in the mechanics of the cochlear partition.

Over the past two decades, observations of 2TS have been made in several studies of cochlear mechanics (Rhode, 1977; Patuzzi *et al.*, 1984; Robles *et al.*, 1989; Ruggero *et al.*, 1992; Nuttall and Dolan, 1993; Rhode and Cooper, 1993; Cooper and Rhode, 1995; Cooper, 1996). Each of these studies has lent considerable support to the hypothesis that at least some of the 2TS which is observed in the cochlear nerve has its origin in the mechanics of the cochlear partition. However, almost all of these studies have concentrated on the basal, high frequency regions of the cochlea. Only one series of mechanical observations has been made relating to 2TS in the apical cochlea (Cooper and Rhode, 1995). These latter observations are qualitatively consistent with the expectation that 2TS should be less strong in the apical turns (see above), but they are too limited to permit quantitative comparison, and provide no information about the 'tuning' of the mechanical 2TS. The present study provides new information regarding the 2TS which occurs in the apical cochlea, and compares this information with that which is already available in the basal turn literature.

METHODS

Mechanical responses to one- and two-tone stimuli were recorded in eight chinchillas (from a total population of 35; only those preparations which were stable for several hours, and in which the mechanical responses to single stimuli were nonlinear, were subjected to two-tone stimulation). The animals were anesthetized using pentobarbital sodium (70mg/kg i.p. initially, with supplementary 1/4 doses as needed thereafter), and body temperatures were maintained near 38°C using a dc controlled heating pad. Lethal overdoses of pentobarbital were administered on completion of the experiments. The care and use of the animals reported in this study were approved by the Animal Care and Use Committee of the University of Wisconsin—Madison.

The cochlear partition was exposed in the third turn of the cochlea, approximately 4mm from its apical termination. A small hole was shaved through the otic capsule to expose the scala vestibuli, and a small puncture or tear was made in Reissner's membrane. Gold-coated polystyrene microbeads (~25µm in diameter; Polysciences Inc.) were then introduced into the scala media, one at a time. When one of these beads came to lie in an appropriate place (on the Hensen's cells, on the lateral portion of the tectorial membrane, or above the central portion of the basilar membrane just lateral to the Hensen's cells), the opening into the scala vestibuli was covered with a flat optical window. Mechanical responses were then monitored using a displacement-sensitive heterodyne laser interferometer (as described by Cooper and Rhode, 1992). The displacement recording system was identical to that described by Cooper (1996).

Stimuli were presented closed-field from two independent transducers: one of these was a reverse-driven condenser microphone cartridge (Brüel and Kjær type 4134 with square-root pre-compensation), and the other was a dynamic loudspeaker (Radio-Shack Super-Tweeter). When tested in a small sealed cavity, the levels of all harmonic and inter-modulation distortion products in the two channel system were at least 50dB below the levels of the primaries. Experimental sound pressure levels were monitored

TABLE I Definition of Terms and Units

F1	Frequency of probe tone	Hz
F2	Frequency of suppressor tone	Hz
L1	Sound pressure level of probe tone	dB SPL ⁽¹⁾
L2	Sound pressure level of suppressor tone	dB SPL ⁽¹⁾
A1s, A1us	Amplitudes of response components locked to F1 in the presence (s, suppressed) and absence (us, unsuppressed) of a suppressor tone.	nm ⁽²⁾
P1s, P1us	Phases of response components locked to F1 in the presence (s, suppressed) and absence (us, unsuppressed) of a suppressor tone.	cycles ⁽³⁾
A2s	Amplitude of response components locked to F2 in the presence of a (potentially suppressive) probe tone.	nm ⁽²⁾
Threshold	L2 necessary to reduce A1s to 90% of A1us	dB SPL ⁽¹⁾
Slope	Maximum rate of change of A1s/A1us with 10dB increase in L2	%/10dB

⁽¹⁾0dB SPL = 0dB re: 20 μ Pa (rms).

⁽²⁾Peak amplitudes are used throughout this paper (peak amplitude = $\sqrt{2} \times$ rms amplitude).

⁽³⁾1 cycle = 2π radians = 360°.

in the ear canal (within 3mm of the umbo) using a probe tube microphone.

Single-frequency tuning and/or input-output functions were determined using short tone-pips (40msec duration including 5msec rise and fall times). Near best frequency [BF \approx 600Hz; see Table I of Rhode and Cooper (1996)] 'probe' tone-pips were then presented at a single level of stimulation while the frequency and level of a second (simultaneously presented) tone-pip were varied. The level of the probe tone stimulation was normally selected to be close to the transition between the low-level 'linear' and mid-range 'compressive' regions of the pure-tone input-output functions (cf. Figs. 1–2). Probe tones at other frequencies and/or levels, or variable level probe tones with fixed level suppressors were also used if sufficient time was available. In most of the two-tone experiments, the duration of the probe tone was 50msec (including 5msec rise and fall times) while that of the second tone (the suppressor) was 30msec (following a 10msec delay; see top panel of Fig. 9 for an example). Longer tone-pips (e.g., 80–120msec) and other temporal patterns were also used in some experiments. Stimulus repetition periods were between 100 and 200msec.

The mechanical responses were digitized at a rate of 50,000 samples per second and averaged across multiple presentations of a given stimulus (typically 32–64 \times). The averaged waveforms were then ana-

lyzed using commercially available software (Matlab®). Table I gives a summary of various terms and factors which were analyzed. The amplitudes and phases of the response components locked to both the probe and suppressor tones were evaluated by fitting sinusoids (at appropriate frequencies) to the steady-state periods of the two-tone responses (typically between 5msec after the onset of the suppressor and 5msec before the end of the suppressor). The analyses were performed using a software implementation of two phase-locked amplifiers acting in quadrature, with the length of the analysis window always being adjusted to include an integer number of stimulation cycles. Control (i.e., unsuppressed) amplitudes and phases were evaluated from the steady-state responses to the probe tone in the period directly preceding the onset of the suppressor tones. The individual control responses were used to evaluate the response changes (i.e., the 2TS) caused by the suppressor tones.

RESULTS

Basic Observations

2TS was defined as a reduction in the magnitude of the response component locked to the frequency of a probe tone during the presentation of a second tone (the suppressor). It should be noted that this definition

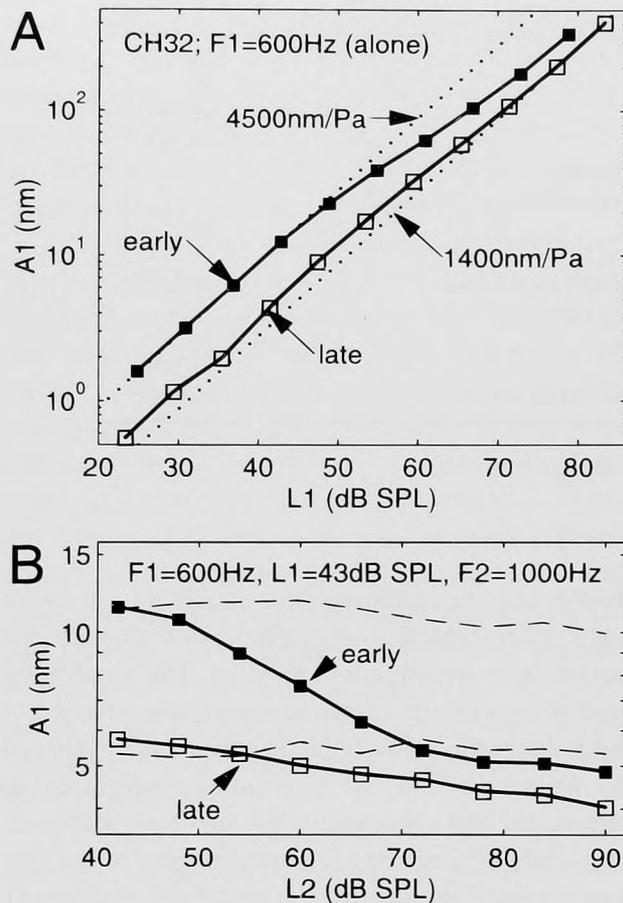


FIGURE 1 Dependence of 2TS on the sensitivity of the cochlea. (A) Input-output functions for a single 600Hz tone measured near the beginning of one experiment (■'s; early) and ~110 minutes later (□'s; late). The two dotted lines show linear input-output functions with sensitivities of 4.5 and 1.4 $\mu\text{m}/\text{Pa}$. These values match those of the 'early' data at low levels, and those of the 'late' data at high levels, respectively. (B) 2TS growth functions measured near the beginning of the same experiment (■'s; early) and ~110 minutes later (□'s; late). Dashed lines indicate 'control' (i.e., unsuppressed) amplitudes observed immediately preceding the onset of the 1000Hz suppressor tones. Solid lines indicate 'suppressed' response amplitudes. More suppression (in either absolute or relative terms) is apparent early in the experiment (i.e., when the preparation exhibits its maximum sensitivity). Experiment: CH32 (BF = 600Hz).

differs from that used in many other 2TS studies (e.g., in most neural studies, and in the mechanical studies of Ruggero *et al.*, 1992).

The amount of 2TS observed in any one preparation was closely related to the degree of compression exhibited in response to single-tone stimuli. To

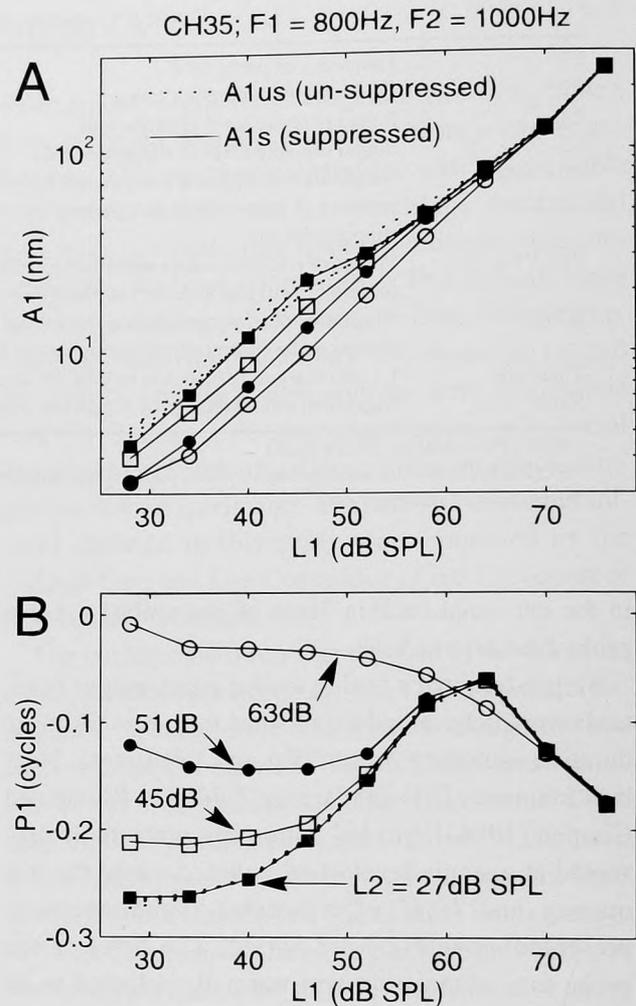


FIGURE 2 Dependence of 2TS on the levels of probe and suppressor tone stimulation. (A) Input-output functions for probe tones (F1 = 800Hz, L1 = 28-76dB SPL) in the presence (solid lines with symbols) and absence (dotted lines, no symbols) of suppressor tones at 4 different sound pressure levels (F2 = 1000Hz, L2 = 27-63dB SPL; see B). (B) Corresponding phase data (phase leads plotted upwards). Experiment: CH35 (BF = 600Hz).

illustrate this, Fig. 1 shows two sets of single-tone input-output functions, and two sets of 2TS growth functions (A1s vs. L2 in this case) from a single experiment. At the beginning of this experiment, the preparation's responses to a single BF tone (600Hz, ■'s, Fig. 1A) grew at a rate of ~0.65dB/dB between ~45 and 65 dB SPL, such that the response sensitivity (expressed in nm/Pa, for example) was ~7.5dB higher below 45dB SPL than it was above

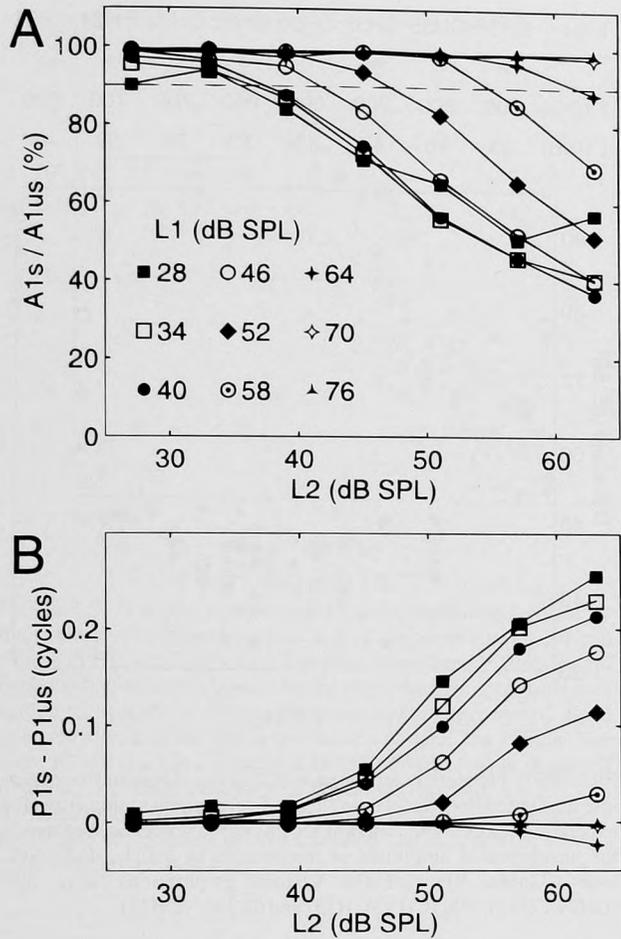


FIGURE 3 2TS growth functions, derived in part from Fig. 2. (A) Amplitude and (B) phase changes caused by various levels of 1000Hz suppressor tone stimulation. Dashed line in A indicates the -10% (i.e., 90% of the unsuppressed response) criterion used to determine 2TS 'thresholds'. Positive phase changes in B indicate phase leads.

70dB SPL. At the same time, a 1000Hz suppressor tone could 'suppress' (i.e., reduce) the responses to a 600Hz 43dB SPL probe tone (■'s, Fig. 1B) to ~50% of their unsuppressed amplitudes (uppermost dashed line in Fig. 1B). Sometime later in the same experiment, the responses to the single 600Hz tones grew in a more nearly linear fashion (□'s, Fig. 1A; the sensitivity below 45dB SPL was only ~2.5dB greater than that above 70dB SPL). At this time, a 1000Hz suppressor tone could only suppress the responses to the 600Hz probe tone (□'s, Fig. 1B) to ~80% of their unsuppressed amplitudes (lowermost

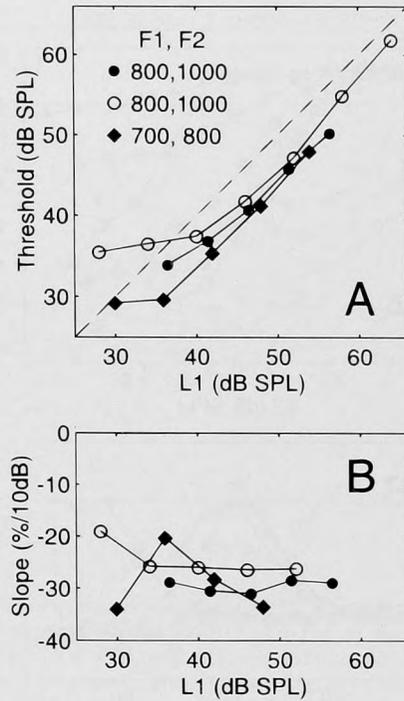


FIGURE 4 Dependence of 2TS on probe tone level. (A) 2TS thresholds and (B) growth function slopes for three data sets. Experiment: CH35 (BF = 600Hz).

dashed line, Fig. 1B). These data are consistent with the idea that the amount of 2TS that can be observed depends on the degree of compression exhibited in response to the single-tone stimuli. The amounts of 2TS observed in different preparations were also consistent with this idea. While some suppression was observed in all eight two-tone experiments, probe tone response amplitudes were reduced by 30% or more in only five animals. The sensitivities of these latter animals were at least 6dB higher below 40dB SPL than above 70dB SPL. No 2TS was observed in control measurements made either (1) from the umbo, or (2) in post-mortem preparations.

Variations with Stimulus Level

The amount of 2TS observed depended on the levels of both the probe and the suppressor tone, as illustrated in Figs. 2-3. In Fig. 2, input-output functions for

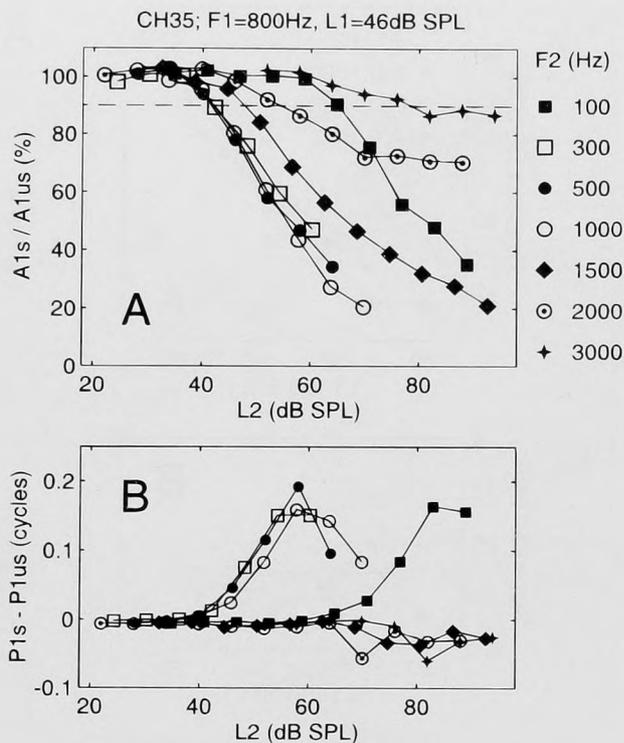


FIGURE 5 Dependence of 2TS on suppressor tone frequency. (A) Amplitude and (B) phase changes caused by suppressor tones covering a wide range of frequencies. Layout as in Fig. 3. Experiment: CH35 (BF = 600Hz, cf. Fig. 2).

an 800Hz probe tone are shown in the presence and absence of a 1000Hz suppressor tone (only four levels of suppressor tone stimulation are illustrated in this figure, with more extensive data provided in Fig. 3; the BF for the preparation illustrated was 600Hz). In the absence of the suppressor tone (dotted lines in Figs. 2A–B), the 800Hz input-output functions can be split into three parts: Up to ~40dB SPL the responses grow more or less linearly, and their phase is approximately constant. Between ~40 and 70dB SPL, the responses grow at ~0.6dB/dB and accumulate ~0.22 cycles (80°) of phase-lead. Above ~70dB SPL, the responses once again grow linearly in amplitude, but the direction of their phase accumulation is reversed. The sensitivity difference between the high- and low-level segments of the (unsuppressed) input-output functions is ~10dB in Fig. 2A. The various suppressor tones illustrated in Fig. 2 have different effects on the

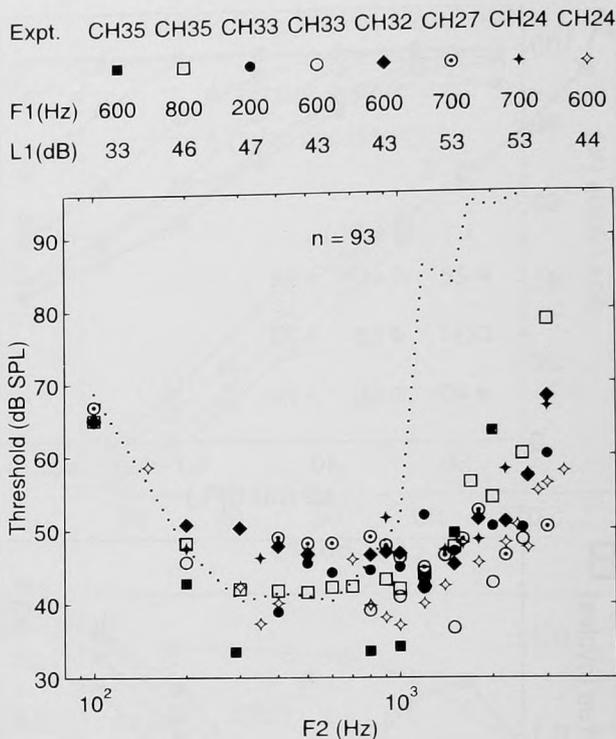


FIGURE 6 Frequency-dependence of 2TS thresholds in five experiments. Dotted line shows a single iso-displacement tuning curve for experiment CH35. The criterion for this curve was chosen to match the unsuppressed amplitude of response to an 800Hz, 46dB SPL tone (22nm). BFs for the various preparations were 500 (CH24/CH33), 600 (CH32/CH35) and 700 Hz (CH27).

three segments of the input-output functions: as the level of the suppressor tone ($L2$) is increased, the sensitivities of the low-level 'linear' and the mid-range 'compressive' segments of the input-output function are reduced, and the slope of the compressive segment is increased (i.e. the responses grow in a more nearly linear fashion across the 40–70dB SPL range). In contrast, the high level (>70dB SPL) segment of the input-output function is affected very little by any of the suppressor tones tested. Increasing levels of 2TS are accompanied by more than 0.2 cycles (72°) of phase-accumulation at low probe levels, with lesser amounts of phase being accumulated during the suppression of the higher level probe tones.

The data of Fig. 2 have been recast (along with additional data) to form a series of suppression growth functions ($A1s/A1us$ vs. $L2$) in Fig. 3. When viewed in this form, the progressive reductions in the probe

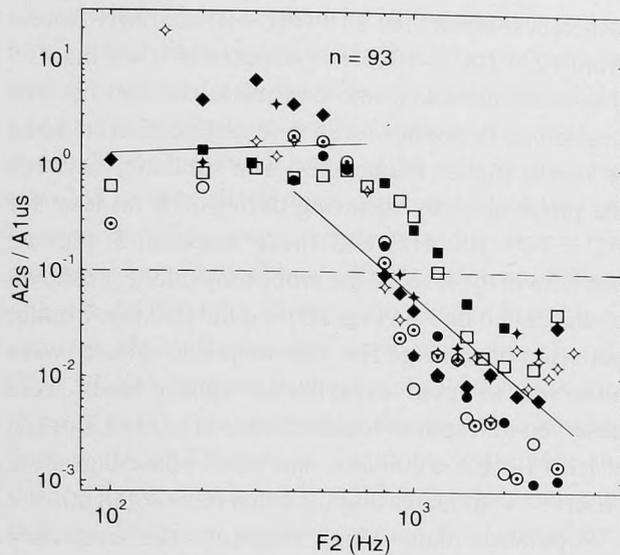


FIGURE 7 Frequency-dependence of displacements evoked by threshold-level suppressor tones in five preparations (legend and BFs as in Fig. 6). Each datum has been normalized by the (un-suppressed) displacements evoked by the probe tone alone (this normalization reduces the amplitude variations across experiments). Solid lines show least square fits to two subsets of data. The leftmost line is for $F2 < F1$; it has a slope of $0.13 (\pm 0.21)$ decades per decade of frequency (\pm values indicate 95% confidence interval, $n = 25$). The rightmost line is for $F2 > F1$; it has a slope of $-2.46 (\pm 0.19)$ decades per decade of frequency ($n = 68$). Dashed line at $A2s/A1us = 0.1$ is used for reference (see text).

tone response amplitudes (Fig. 3A) and the accumulations of phase (Fig. 3B) caused by increasing levels of suppressor tone stimulation are obvious. It is also apparent that as the level of the probe tone (L1) is increased, the threshold for 2TS [i.e., the level at which the curves intersect the 90% response criterion (dashed line) in Fig. 3A; cf. Table I] increases. This is particularly true for probe tones which fall in the compressive region of the input-output functions in Fig. 2A (i.e., for $L1 > 40$ dB SPL). In contrast, the slopes of the 2TS growth functions vary very little with the level of the probe tone once the threshold for 2TS is exceeded. These points are illustrated more explicitly, and combined with additional data in Fig. 4. It is evident that the thresholds for 2TS increase in direct proportion to the level of the probe tone (i.e., at a rate of ~ 1 dB/dB, cf. Fig. 4A) when the probe tones lie in the compressive region of the preparation's input-output function (cf. Fig. 2A). However, the 2TS thresholds appear to be fixed (i.e., independent of L1) when the

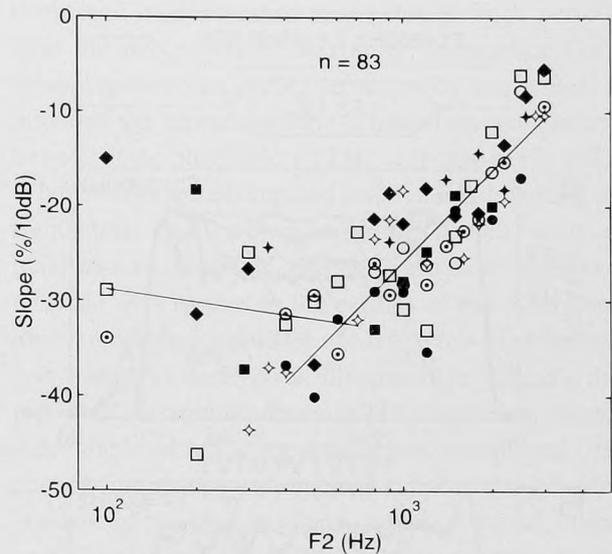


FIGURE 8 Frequency-dependence of 2TS growth function slopes in five preparations (legend and BFs as in Fig. 6). Each slope was calculated across a 10dB range of levels and represents the steepest part of the 2TS growth function occurring anywhere from 6dB below threshold to 16dB above threshold (data sets extending less than 10dB above threshold were excluded from the analysis). Solid lines show least square fits to two subsets of data. The leftmost line is for $F2 < F1$; it has a slope of $-4 (\pm 4)$ % per decade of frequency (\pm values indicate 95% confidence interval, $n = 21$). The rightmost line is for $F2 > F1$; it has a slope of $32 (\pm 2)$ % per decade of frequency ($n = 62$).

probe tones lie in the low-level linear regions of the input-output functions (i.e. below ~ 40 dB SPL; cf. Fig. 2A).

Variations with Suppressor Tone Frequency

Various characteristics of the 2TS phenomenon depended on the frequency of the suppressor tone ($F2$), as illustrated in Figs. 5–9. In Fig. 5, the amplitude and phase changes which accompanied the suppression of an 800Hz, 46dB SPL probe tone are shown as a function of increasing L2 (the BF for the preparation illustrated here was 600Hz). Both the thresholds for 2TS (see Table I), the rates of growth of 2TS with increasing L2, and the phase-changes which accompany the 2TS vary systematically with the frequency of the suppressor tone. The 2TS thresholds are fairly constant from 300–1000Hz, but increase progressively both above and below this range (only a small subset of the data on which this statement is based are

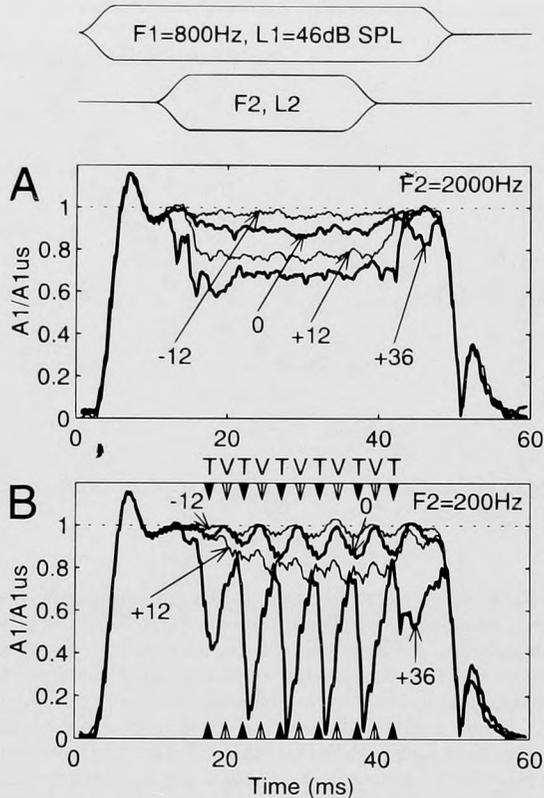


FIGURE 9 Time-course of 2TS effects caused by high (A) and low (B) frequency suppressor tones. Labelled arrows give suppressor tone levels in dB re 'threshold' (54dB SPL in A, 48dB SPL in B). Each panel shows the results of fitting one period of an 800Hz sinusoid to various sub-sections of the filtered two-tone responses. Each sub-section of the response was 1.25msec (i.e., $1/800\text{Hz}$) wide, and was offset by $200\mu\text{sec}$ with respect to the previous sub-section (the first sub-section began at time zero). Pre-filtering was used merely to remove the excitation caused by the suppressor tones: the data were initially oversampled ($2\times$) to obtain an integer number of samples per period; each waveform was then passed through a 4th order Butterworth filter twice, once in reversed time-order, to minimize any distortion of the response phase. The resulting data have been normalized with respect to their amplitudes in the period prior to the onset of the suppressor tone. The points marked V and T in panel B indicate the instants of maximal suppressor-induced displacement towards the scala vestibuli and scala tympani (respectively). Envelopes of the two stimuli are shown above panel A (combined acoustic and travelling wave delays shifted the excitatory responses by $\sim 4\text{msec}$ (F1) and 5msec (F2) with respect to the illustrated envelopes). Experiment: CH35 (BF = 600Hz).

illustrated in Fig. 5—more complete data are summarized in Figs. 6–8). The rate of growth of 2TS (above the various suppression thresholds) is also fairly constant up to $F2 \approx 1000\text{Hz}$, but then decreases progressively with further increases in $F2$. The phase-changes

which accompany the 2TS (Fig. 5B) are fairly similar from $F2 = 100$ to 1000Hz (particularly when the 2TS thresholds are taken into consideration), but become negligible, or perhaps even reverse direction (tending to lag) at higher frequencies. The similarity between the phase-changes occurring during 2TS (at least for $F2 = 100\text{--}1000\text{Hz}$) and those associated with an *increase* in the level of the probe tone (alone, as shown by the dotted lines in Fig. 2B) is quite striking. Similar patterns of change in the response phase were observed in most experiments (phase-leads were observed in response to an increase in either $L1$ or $L2$, at least for $F2 < 2000\text{Hz}$; and small phase-lags were observed with increasing $L2$ when $F2 > 2000\text{Hz}$).

Population data which illustrate the frequency dependencies of the suppression thresholds, the cochlear partition displacements evoked by threshold-level suppressor tones, and the rates of growth of 2TS with increasing $L2$, are given in Figs. 6–8, respectively. All of the preparations illustrated in these figures had BFs in the 500–700Hz range. The probe tones varied from just below the BF (e.g., the $F1 = 200\text{Hz}$ data for CH33) to just above the BF (the $F1 = 800\text{Hz}$ data for CH35), but the 2TS response characteristics depended similarly on the absolute frequency of the suppressor (i.e., $F2$) in every case.

A single iso-displacement contour (i.e., a mechanical tuning curve derived using single-tone stimuli) for one preparation is shown for reference (dotted line) in Fig. 6. The 2TS thresholds (as indicated by the various symbols in Fig. 6) are seen to follow this contour quite closely up to $\sim 800\text{Hz}$ (this is particularly true for the data indicated by the \square 's, which were observed in the same experiment as the single-tone data). There is a large discrepancy between the 2TS and single-tone data at frequencies above 800Hz , however. This discrepancy indicates that the high-frequency suppressor tones could cause threshold amounts of 2TS at sound pressure levels which were 'effectively' much lower than those observed at lower frequencies (i.e., at levels which evoked much lower displacements at the cochlear location under study).

The above findings are expanded and clarified by the data shown in Fig. 7. In this figure, the displacements evoked by the various threshold-level suppressor

tor tones have been normalized by the relevant probe-tone evoked displacements (this procedure reduces the scatter associated with the different sensitivities of the various preparations, as well as some of the variation due to differences in the levels of the individual probe-tones). The normalized displacements (A_{2s}/A_{1us}) are seen to decrease progressively with increasing frequency, particularly above $\sim 800\text{Hz}$ (95% confidence intervals for the $F2 > F1$ regression line in Fig. 7 indicate a significantly negative slope, while those for the $F2 < F1$ line indicate insignificant difference from a slope of zero). It is noteworthy that all of the low-frequency ($F2 < F1$) data in Fig. 7 lie well above the dashed line indicating $A_{2s}/A_{1us} = 0.1$: this indicates that the combined responses to the two-tone stimuli were always larger than the (unsuppressed) responses to the probe tones when $F2 < F1$ (recall that the 2TS 'thresholds' were defined when $A_{1s}/A_{1us} = 0.9$; hence for $A_{2s}/A_{1us} > 0.1$ in Fig. 7, $A_{2s} + A_{1s} > A_{1us}$).

Figure 8 shows a clear trend for lower rates of growth of 2TS with increasing suppressor tone frequency, particularly for $F2 > F1$. The rates of growth of 2TS do not appear to depend on frequency when $F2 < F1$, but the data are limited and the scatter is large at low frequencies (e.g., below 400Hz). 95% confidence intervals for the $F2 > F1$ regression line indicate a significantly positive slope (note the polarity of the ordinate in Fig. 8), while those for the $F2 < F1$ line indicate insignificant difference from a slope of zero.

Temporal Aspects of 2TS

The 2TS effects observed in most experiments began within 1 msec of the onset of the excitatory responses to the suppressor tone, remained fairly constant through the steady-state periods of stimulation, and ended within 1–2 msec of the excitatory response offsets (cf. Fig. 9A). However, when the suppressor tones were sufficiently low in frequency (e.g., $100\text{--}200\text{Hz}$, cf. Fig. 9B), the responses to the probe tones could be reduced in a phasic manner. In the example of Fig. 9B, the probe tone responses decreased and increased only once during each period of suppressor tone stimulation. In other cases, however, the probe tone responses

decreased and increased twice during each period, with the two points of maximum suppression (i.e., minimum response) being separated by one-half of a period of the suppressor tone (a hint of this pattern can be seen in the 'threshold + 12dB' response of Fig. 9B). When results were compared across animals (or across frequencies in a given animal), the phases of either maximum or minimum suppression did not appear to be fixed with respect to the periods of the suppressor tones (more data would be needed to reveal an underlying pattern). Indeed, as illustrated in Fig. 9B, the phases of maximum/minimum 2TS could even change when the level of the suppressor tone was altered (the changes in the suppression phases appeared to be independent of the phase-changes which occurred in the excitatory responses to the suppressor tones themselves; cf. Rhode and Cooper, 1996).

DISCUSSION

Many of the characteristics revealed in the present report are similar to those described in previous reports of 2TS in the basal mammalian cochlea. In particular:

(1) 2TS appears to depend on the physiological condition of the apical cochlea, just as it does in the basal cochlea. The evidence of this dependence is circumstantial, but quite convincing: 2TS is only observed in the living cochlea and its magnitude correlates strongly with the degree of nonlinearity, sensitivity, or 'activity' (see Introduction) expressed in the cochlear partition's responses to pure tones (cf. Fig. 1, and also Ruggiero *et al.*, 1992).

(2) Low frequency suppressor tones ($F2 < F1$) suppress the responses to near-BF probe tones at a greater rate than high frequency suppressor tones ($F2 > F1$) do (cf. Figs. 5 and 8). Different growth rates for the suppression caused by above- and below-BF tones have previously been demonstrated in the basal turns of chinchilla (Ruggiero *et al.*, 1992), guinea-pig (Nuttall and Dolan, 1993; Cooper, 1996) and cat cochleae (Rhode and Cooper, 1993). Various electrophysiological studies suggest that similar relationships between the above- and below-BF suppressors exist throughout

the cochlea (e.g., Abbas and Sachs, 1976; Javel *et al.*, 1983; Delgutte, 1990). In quantitative terms, the rates of growth of 2TS observed in the present report are considerably smaller than those observed in previous studies of cochlear mechanics: the average slope for our low frequency ($F2 < F1$) 2TS growth functions (Fig. 8) is $-31\%/10\text{dB}$, or -0.32dB/dB , while that reported in previous (basal turn) studies is $\sim 1\text{dB/dB}$. As pointed out in the Introduction, such a variation in the rate of growth of 2TS with cochlear location might be expected by analogy with recent findings in the cochlear nerve (Delgutte, 1990). Due to the potentially confounding effects of the variations in 2TS with physiological condition (see point 1, above), however, some caution must be applied to these quantitative (mechanical) comparisons.

(3) Threshold-level suppressor tones appear to evoke a constant displacement of the cochlear partition at the BF site, at least when $F2 < BF$ and $L1$ is fixed (cf. Figs. 6–7). This has been demonstrated directly in the basal turn of the guinea-pig cochlea (Cooper, 1996), and has been suggested in various electrophysiological and theoretical studies (e.g., see Patuzzi *et al.*, 1989). [Ruggero *et al.* (1992) have reported a closer association between BM *velocity* and 2TS thresholds (at least for $F2 < BF$) in the basal turn of the chinchilla cochlea, but this finding has since been judged as equivocal—see Cooper, 1996]. It might also be pointed out that the displacements evoked by the threshold-level suppressors were consistent with the hypothesis that 2TS occurs whenever the cochlear partition is pushed into its ‘compressive’ region of response (cf. Patuzzi *et al.*, 1989; Geisler *et al.*, 1990). Since most of the present data were collected using probe tones which fell at the border of this compressive region (see Methods), however, they do not provide an objective test of this hypothesis.

(4) Threshold-level suppressor tones cause much less displacement of the cochlear partition at the BF site when $F2 > BF$ than when $F2 < BF$ (cf. Figs. 6–7). This finding is consistent with that demonstrated directly in the basal turn of the guinea-pig cochlea (Cooper, 1996). It is also consistent with a suggestion made in various mechanical, electrophysiological and theoretical studies, namely that the site responsible for

2TS (and various other manifestations of the cochlea’s non-linearity) is located basally to the most sensitive (i.e., BF) site, where the displacements caused by both above- and below-BF suppressor tones are expected to be more similar (at the suppression thresholds; see Geisler *et al.*, 1990).

(5) Both above- and below-BF suppressor tones can alter the phase characteristics of the responses to near-BF probe tones. The apical turn data of the present report (cf. Fig. 5) are particularly similar to those observed in the hook regions of both cat and guinea-pig cochleae (Rhode and Cooper, 1993; Cooper, 1996) in this respect: most of the suppressor induced changes involved phase-leads, and most of these were consistent with the phase-changes observed when the level of the probe-tone (alone) was *increased* (cf. Figs. 2B/5B). These findings are not completely unexpected, since both stimulus manipulations (*adding* a suppressor tone, or *increasing* the level of a single near-BF probe tone) are capable of reducing the sensitivity of the cochlear partition by similar amounts (see Cooper, 1996). However, not all of the suppressor induced phase-changes were consistent with the effects of increasing the level of the probe tone, either in the present report (see Results), or in the first turn of the guinea-pig cochlea (Nuttall and Dolan, 1993). Moreover, both Ruggero *et al.* (1992) and Nuttall and Dolan (1993) have observed 2TS to induce different phase-changes (i.e., leads and/or lags) in the responses to a given probe tone depending on whether the suppressor tone frequency was higher or lower than the probe tone (or the BF). Similar inconsistencies (or peculiarities) have also been noted in the phase data of many electrophysiological studies (e.g., Cheatham and Dallos, 1989, 1990, 1992; Deng and Geisler, 1985; Nuttall and Dolan, 1993). These data are not easy to explain, even though similarly peculiar results can be generated by certain classes of cochlear models (e.g., see Kanis and de Boer, 1994). In the view of the present authors, the different phase behaviors described both within and across these various studies emphasize the shortcomings of our present understanding of the cochlea.

(6) Very low frequency suppressor (or ‘bias’) tones can modulate the responses to a near-BF probe

tone in a phasic manner. This has previously been demonstrated in the basal turn of the guinea-pig (Patuzzi *et al.*, 1984; Cooper, 1996; Geisler and Nuttall, 1996), cat (Rhode and Cooper, 1993), and chinchilla cochlea (Ruggero *et al.*, 1992). Most of the basal turn data imply that the suppressive effects of the low-frequency tones are mediated almost instantaneously through the *displacements* of the cochlear partition from its resting (baseline) position (displacements towards the scala tympani usually causing maximal amounts of 2TS at near-threshold levels; even the data of Ruggero *et al.*, 1992, which appear to show maximal suppression at the instants of maximal BM *velocity*, can be interpreted in this way—see Cooper, 1996). Some of the apical turn data in the present report are consistent with this view (e.g., see the curves labelled -12 and 0dB in Fig. 9B), but others are not.

One final point, which relates directly to the main aims set out in the Introduction, is that the 'tuning' of the mechanical 2TS phenomena appears particularly broad in the apical turn of the cochlea (Fig. 6). Mechanical data relating to the issue of 2TS tuning in the basal cochlea show that the BM's suppression thresholds vary in much the same way (with frequency) as its excitation thresholds do (Rhode and Cooper, 1993; Cooper, 1996). There is some indication that the suppression tuning curves may be displaced towards higher frequencies than the excitation tuning curves, but this effect is much more apparent in the apical turn (present report; Fig. 6) than in the base. At first sight, the differences between the mechanics in the apical and basal cochlea appear to be consistent with observations made at the level of the cochlear nerve (Prijs, 1989; as described in the Introduction). However, any quantitative comparisons between the neural and mechanical tuning curves must be viewed with caution. In this case, the mechanical suppression thresholds are not only subject to the effects of physiological vulnerability (cf. point 1, above); the shapes of the 2TS tuning curves are also highly dependent on the criterion which is used to determine the 2TS threshold (recall that the slopes of the 2TS growth functions are a strong function of F2, as shown in Figs. 5 and 8).

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References

- Abbas, P. J. and Sachs, M. B. (1976). Two-tone suppression in auditory-nerve fibers: Extension of a stimulus-response relationship. *J. Acoust. Soc. Am.* **59**, 112–122.
- Cheatham, M. A. and Dallos, P. (1989). Two-tone suppression in inner hair cell responses. *Hear. Res.* **40**, 187–196.
- Cheatham, M. A. and Dallos, P. (1990). Comparison of low- and high-side two-tone suppression in inner hair cell and organ of Corti responses. *Hear. Res.* **50**, 193–210.
- Cheatham, M. A. and Dallos, P. (1992). Two-tone suppression in inner hair cell responses: Correlates of rate suppression in the auditory nerve. *Hear. Res.* **60**, 1–12.
- Cooper, N. P. (1996). Two-tone suppression in cochlear mechanics. *J. Acoust. Soc. Am.* **99**, in press.
- Cooper, N. P. and Rhode, W. S. (1992). Basilar membrane mechanics in the hook region of cat and guinea-pig cochleae: Sharp tuning and nonlinearity in the absence of baseline position shifts. *Hear. Res.* **63**, 163–190.
- Cooper, N. P. and Rhode, W. S. (1995). Nonlinear mechanics at the apex of the guinea-pig cochlea. *Hear. Res.* **82**, 225–243.
- Dallos, P. (1992). The active cochlea. *J. Neurosci.* **12**, 4575–4585.
- Delgutte, B. (1990). Two-tone rate suppression in auditory-nerve fibers: Dependence on suppressor frequency and level. *Hear. Res.* **49**, 225–246.
- Deng, L. and Geisler, C. D. (1985). Changes in the phase of excitor tone responses in cat auditory nerve fibers by suppressor tones and fatigue. *J. Acoust. Soc. Am.* **78**, 1633–1643.
- Geisler, C. D. and Nuttall, A. L. (1996). Two-tone suppression in basilar-membrane responses. Abstracts of the 19th Midwinter Meeting of the Association for Research in Otolaryngology, #221, p56.
- Geisler, C. D., Yates, G. K., Patuzzi, R. B. and Johnstone, B. M. (1990). Saturation of outer hair cell receptor currents causes two-tone suppression. *Hear. Res.* **44**, 241–256.
- Javel, E., McGee, J., Walsh, E. J., Farley, G. R. and Gorga, M. P. (1983). Suppression of auditory-nerve responses. II. Suppression threshold and growth, iso-suppression contours. *J. Acoust. Soc. Am.* **74**, 801–813.
- Kanis, L.-J. and de Boer, E. (1994). Two-tone suppression in a locally active nonlinear model of the cochlea. *J. Acoust. Soc. Am.* **96**, 2156–2165.
- Nuttall, A. L. and Dolan, D. F. (1993). Two-tone suppression of inner hair cell and basilar membrane responses in the guinea-pig. *J. Acoust. Soc. Am.* **93**, 390–400.
- Patuzzi, R. B. and Robertson, D. (1988). Tuning in the mammalian cochlea. *Physiol. Rev.* **68**, 1009–1082.
- Patuzzi, R. B., Sellick, P. M. and Johnstone, B. M. (1984). The modulation of the sensitivity of the mammalian cochlea by low frequency tones. III—Basilar membrane motion. *Hear. Res.* **13**, 19–27.
- Patuzzi, R. B., Yates, G. K. and Johnstone, B. M. (1989). Outer hair cell receptor current and sensorineural hearing loss. *Hear. Res.* **42**, 47–72.

- Prijs, V. F. (1989). Lower boundaries of two-tone suppression regions in the guinea-pig. *Hear. Res.* **42**, 73–81.
- Rhode, W. S. (1977). Some observations of two-tone interactions measured using the Mössbauer effect. In: *Psychophysics and physiology of hearing*, E. F. Evans and J. P. Wilson, eds., Academic Press (New York), 27–38.
- Rhode, W. S., Geisler, C. D. and Kennedy, D. T. (1978). Auditory nerve fiber responses to wide-band noise and tone combinations. *J. Neurophysiol.* **41**, 692–704.
- Rhode, W. S. and Cooper, N. P. (1993). Two-tone suppression and distortion production on the basilar membrane in the hook region of cat and guinea-pig cochleae. *Hear. Res.* **66**, 31–45.
- Rhode, W. S. and Cooper, N. P. (1996). Nonlinear mechanics in the apical turn of the chinchilla cochlea in vivo. *Auditory Neuroscience*, in press.
- Robles, L., Ruggero, M. A. and Rich, N. C. (1989). Nonlinear interactions in the mechanical response of the cochlea to two-tone stimuli. In: *Cochlear mechanisms: structure, function and models*, J. P. Wilson and D. T. Kemp, eds., Plenum Press, N.Y., 369–375.
- Ruggero, M. A., Robles, L. and Rich, N. C. (1992). Two-tone suppression in the basilar membrane of the cochlea: Mechanical basis of auditory-nerve rate suppression. *J. Neurophysiol.* **68**, 1087–1099.
- Sachs, M. B. and Young, E. D. (1980). Effects of nonlinearities on speech encoding in the auditory nerve. *J. Acoust. Soc. Am.* **68**, 858–875.