Frequency-dependent self-induced bias of the basilar membrane and its potential for controlling sensitivity and tuning in the mammalian cochlea[a]

Eric L. LePage[b]

Departments of Otolaryngology and Biomedical Engineering, 80 E. Concord Street, R903, Boston, Massachusetts 02118

A displacement-sensitive capacitive probe technique was used in the first turn of guinea pig cochleas to examine whether the motion of the basilar membrane includes a displacement component analogous to the dc receptor potentials of the hair cells. Such a "dc" component apparently exists. At a given location on the basilar membrane, its direction toward scala vestibuli (SV) or scala tympani (ST) varies systematically with frequency of the acoustic stimulus. Furthermore, it appears to consist of two parts: a small asymmetric offset response to each gated tone burst plus a progressive shift of the basilar membrane from its previous position. The mean position shift is cumulative, increasing with successive tone bursts. The amplitude of the immediate offset response, when plotted as a function of frequency, appears to exhibit a trimodal pattern. This displacement offset is toward SV at the characteristic frequency (CF) of the location of the probe, while at frequencies either above or below the CF the offset is relatively larger, and toward ST. The mechanical motion of the basilar membrane therefore appears to contain the basis for lateral suppression. The cumulative mean position shift, however, appears to peak toward ST at the apical end of the traveling wave envelope and appears to be associated with a resonance, not of the basilar membrane motion directly, but coupled to it. The summating potential, measured concurrently at the round window, shows a more broadly tuned peak just above the CF of the position of the probe. This seems to correspond to the peak at the CF of the mechanical bias. As the preparation deteriorates, the best frequency of the vibratory displacement response decreases to about a half-octave below the original CF. There is a corresponding decrease in the frequency of the peaks of the trimodal pattern of the asymmetric responses to tone bursts. The trimodal pattern also broadens. In previous experiments the basilar membrane has been forced to move in response to a low-frequency biasing tone. The sensitivity to high-frequency stimuli varies in phase with the biasing tone. The amplitudes of slow movement in these earlier experiments and in the present experiments are of the same order of magnitude. This suggests strongly that the cumulative shift toward ST to a high-frequency acoustic stimulus constitutes a substantial controlling bias on the sensitivity of the cochlea in that same high-frequency region. Its effect will be to reduce the slope of neural rate-level functions on the high-frequency side of CF.

PACS numbers: 43.63.Kz, 43.63.Wj, 43.63.Bq

INTRODUCTION

The description of the traveling wave motion of the basilar membrane by von Békésy (1960) has undergone a series of modifications due to developments in direct measurement technique. The introduction of the Mössbauer technique by Johnstone and Boyle (1967) showed a significant increase in the tuning of a point of the basilar membrane in the guinea pig. Their results were extended to the squirrel monkey by Rhode (1971), who showed that the tuning characteristics were nonlinear and that the nonlinearity disappeared with the death of the preparation. Moreover, the nonlinear behavior appeared to be responsible for the apparent increase in frequency tuning for low sound levels. A careful study in guinea pigs by Wilson and Johnstone (1975), however, showed remarkable linearity over a wide range of sound levels and over a wide range of frequencies. Since they had monitored the neural compound action potential to clicks, the result remains intriguing, particularly since Rhode (1978) repeated the measurement in guinea pigs and again found no discernible nonlinear behavior. This implied that either there was a species difference which seemed unlikely, a place difference which seemed less likely, or possibly a difference in experimental methodology, e.g., dependence of the appearance of the nonlinear behavior on the technique.

The issue was resolved by LePage and Johnstone (1980). Using a capacitive probe they showed that nonlinear behavior was observable in the first turn of guinea pig coch-

---

lea. Moreover, it was qualitatively similar to the nonlinear behavior of the squirrel monkey (Robles et al., 1976). The same study (LePage, 1981) also showed that the nonlinear behavior not only disappeared with death of the preparation, but that the input–output slope was correlated ($\rho = 0.7$) with the threshold of the compound action potential to tone bursts at the characteristic frequency (LePage and Johnstone, 1981a), suggesting that deafness was in some way tied to loss of the nonlinear behavior. This lead to more sensitive measurements of cochlear tuning, as in Khanna and Leonard (1982), who showed sharper tuning at lower levels; while Sellick et al. (1982) duplicated the nonlinear picture developed using the capacitive probe and, using a more sensitive Mössbauer technique, showed sharp tuning remarkably similar to neural tuning.

The most important aspect of the LePage (1981) study was that the nonlinear compression appeared to be mirrored in the baseline position of the basilar membrane. At that stage, the phenomenon was poorly understood, and the experimental design did not allow for a proper characterization of the baseline position; however, the data did carry the suggestion that significant baseline movements did occur, and over relatively short time spans.

The mechanical description and resultant models have remained restricted to the vibratory motion of the traveling wave (deBoer and Viergever, 1983; Allen et al., 1986). On the other hand, the sensory hair cells are sensitive to static mechanical deformation of the stereocilia (Flock, 1971; Hudspeth and Corey, 1977) so that any low-frequency component of basilar membrane motion, if it exists, must also be considered an adequate stimulus to the sensory cells. The sharp tuning of single neurons of the auditory nerve is primarily attributable to depolarizing dc receptor potentials of the inner hair cells (IHCs) (Russell and Sellick, 1978), particularly for frequencies above 4 kHz where the mechanical tuning is sharpest.

While IHC depolarization must be attributable to some form of rectification, the exact nature of the rectifying mechanism is not known. Two potential mechanisms exist.

Hair cells themselves possess a nonlinear transfer characteristic (Hudspeth and Corey, 1977; Russell et al., 1986), which may account for nonlinear rectification of vibratory displacements. However, at threshold levels, the vibratory excursions of the basilar membrane are only 0.35 nm (Sellick et al., 1982). Recent reports suggest that the sensitivity of mammalian hair cells may be much greater than the sensitivity of amphibian hair cells (Russell, 1985), yet it would seem that threshold displacements are still too small (by one to two orders of magnitude) to account for the millivolts of depolarization of IHCs required to stimulate the nerve. For vibratory movements less than about 10 nm small signal conditions will apply (Russell et al., 1986, Fig. 5C) and no net rectification will occur.

The second possibility (Russell and Ashmore, 1983) is that IHC depolarization may be due primarily to a physical displacement of the cochlear partition from its mean position, which results in mechanical deformation of the IHC stereocilia. Active amplification produced by the outer hair cells (OHC) (Davis, 1983; Neely and Kim, 1983; Mountain

et al., 1983; Mountain, 1986) produces an "ac" amplitude of the motion sufficiently large to be rectified by the OHC. For example, if the stiffness of the OHC stereocilia is a function of OHC membrane potential (LePage, 1981; McMullen and Mountain, 1985) and force generation by the OHC likewise (Mountain, 1986), the receptor potentials of the OHC may introduce a "dc" component to the motion of the tectorial and basilar membranes. If the dc receptor potentials of the IHCs are attributable to dc displacements of the cochlear partition, the displacements should be detectable by displacement-sensitive techniques. Most of the data obtained so far has come from techniques which are velocity sensitive, such as the Mössbauer technique. One of the disadvantages of the Mössbauer technique is the slowness of the gamma ray counting procedures. By comparison the capacitive probe offers a direct measure of the basilar membrane motion in real time as an electrical signal which can be observed visually and aurally.

Reports from indirect, acoustic emission experiments (Kemp, 1978) show that the mechanical properties of the cochlear partition are influenced by noise (Zurek and Clark, 1981), injection of furosemide (Hubbard et al., 1986), and electrical manipulations of the organ of Corti, either by efferent stimulation (Mountain, 1980; Siegel and Kim, 1982; Brown et al., 1983) or by passing current (Hubbard and Mountain, 1983). It is likely, therefore, that the electrical depolarization produced by normal acoustic stimulation may produce a net mechanical displacement of the cochlear partition in ways yet to be fully described.

There appear to be at least four possible sources of force generation in the organ of Corti. All are associated with the OHCs. First, there is evidence of contractile proteins in the apical regions of the IHCs (Flock, 1980; Flock et al., 1982; McCartney et al., 1980). Second is the possibility that the OHC stereocilia themselves may be able to generate an active force (Wiederhold, 1976; Weiss, 1982; Ashmore, 1985). Third, Brownell et al. (1985) have observed OHC body motile behavior in response to changes in external electric fields by some electrokinetic process. The fourth possibility (LePage, 1981, 1987b) is that one of the functions of the stria vascularis is to control the osmotic pressure in scala media so that effects such as a localized reduction in stereocilia stiffness, proportional to hair cell membrane potential, could produce a net movement of the cochlear partition. This also carried the implication that depolarizations in a small number of hair cells could control a large amount of potential energy in the form of changes in osmotic pressure. Such a scheme would be generally in keeping with the Davis model (1958) and would result in large changes in the baseline position of the basilar membrane, which would be transmitted to the inner hair cell stereocilia via the arches and tectorial membrane.

If the receptor potentials do have a mechanical correlate, it seems likely that their polarity will vary in some systematic way, which might correlate with the frequency and intensity dependence of the intracellular potentials (Russell et al., 1986) and extracellular potentials (Davis et al., 1958; Dallos et al., 1972).

The data presented here were obtained using the same

capacitive probe technique (LePage, 1987a) as the earlier study (LePage and Johnstone, 1980), but with the specific *objective* of examining basilar membrane waveform responses to tone bursts in low threshold preparations. The data are consistent with the earlier finding (LePage, 1981) that mechanical baseline changes occur in response to high-frequency stimuli and give a number of clues as to their function.

I. METHODS

The results presented here are taken from a series of experiments employing 32 guinea pigs. Following anesthetization, the animals were paralyzed with Flaxedil to prevent middle ear muscle response to sound and were artificially respired. The Flaxedil was effective in eliminating visible movements of the ossicles due to contraction of the tensor tympani muscle. Perilymph was removed from scala tympani for the 2 min of data collection using gentle suction via a wick. The 100-μm tip of the capacitive probe was located 2–3 μm from the basilar membrane, about 3.5 mm from the base of the cochlea.

The stimuli were a set of ten digitally synthesized 12-ms tone bursts with 1-ms rise and fall times and repeated with a stimulus period of 27.7 ms. Each burst followed a 3-ms silent interval from the beginning of the period. The stimulus frequencies were set to be close to -2, -1, -0.5, -0.25, -0.1, 0, $+0.08$, $+0.16$, $+0.23$, and $+0.3$ oct, respectively, relative to the estimated CF of the place being measured.

The two-channel analog sampling of the mechanical and electrical responses were interleaved on a 6.75-μs time step. The response to every other burst was sampled synchronously with the stimulus period for 64, 144, or 400 repetitions and the average determined. In sampling 144 responses, each series of trials took about 2 min to complete, or about 10 s per frequency. The capacitive probe amplifier was ac coupled with a time constant of 40 ms (LePage, 1987a). Consequently, in the resulting averaged records, consideration is given to three components of the displacement response in three different frequency ranges. The highest frequency range corresponds to the "ac" or vibratory component at the stimulus frequency.

Second, any "dc pedestal" or baseline offset response coincident with the tone burst, which appears in the final average, is plotted versus frequency. In each case, this value is the difference of the averaged values of the 222 sampled bins before the response and the 888 bins during the response. This procedure produces a further signal-to-noise improvement of ca. 20 dB so that, based on the baseline during the silent period, the effective noise level is ca. 0.01 nm. The vibratory amplitudes are obtained by computing the Fourier coefficient of the fundamental component in the waveform during the burst. This produces a further 35- to 40-dB signal-to-noise improvement,[1] so that the Fourier component noise level is less than 1 pm. The vibratory and baseline offset patterns, plotted as a function of frequency, are therefore significant despite the small size. The pedestal is also referred to as the "short-term" dc response.
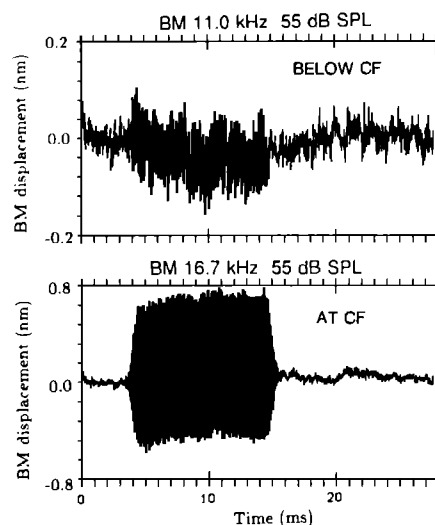

FIG. 1. Demonstration of the bipolar nature of the displacement offset of the basilar membrane to a 12-ms, 55dB SPL tone burst for 144 averaged responses in a sequence of 288 repetitions of the tone burst. The top panel shows the response one half-octave below the CF of the place being measured, whereas the lower panel shows the response at CF. A small asymmetry is evident in both records, which while labile, is representative of the set of preparations. Positive is toward SV and negative is toward ST. The asymmetry amounts to fractions of a nanometer displacement.

Third, there is consideration of any steady shift in the baseline response, which also appears in the final average due to frequencies in the response *below* the repetition frequency of the tone burst presentations. Such a component of the response constitutes an incremental shift of the mean position of the basilar membrane, which "*summates*" to a net value over the trial period of about 10 s. Due to the ac coupling of the capacitive probe signal at 4 Hz, the averaged responses do not retain absolute values of basilar membrane position. Instead, the average represents any behavior which sums over the stimulus period and is also referred to as the "long-term" component.

All tones were delivered by a Beyer DT48 dynamic earphone at precorrected sound levels (dB *re*: 20 μPa) at the tympanum, with the corrections derived from a sound calibration carried out at the beginning of each experiment. Sound levels in excess of 80 dB were mostly avoided since high sound levels have been shown to disable nonlinear mechanical behavior (LePage, 1981; Patuzzi *et al.*, 1984a). In order to keep track of the condition of the preparation, the N_1 threshold was determined for the fixed set of ten stimulus frequencies at about hourly intervals for the 3- to 5-h duration of the experiment. In addition to periodic audiometric determination of thresholds, the round window potential was recorded simultaneously with the mechanical measurements on a second channel to obtain an extracellular measure of hair cell electrical response. Frequency series were interspersed with intensity series. The latter provided the values of drained N_1 thresholds quoted throughout the present paper.

Q_{10dB} = 4.3

DC

AC

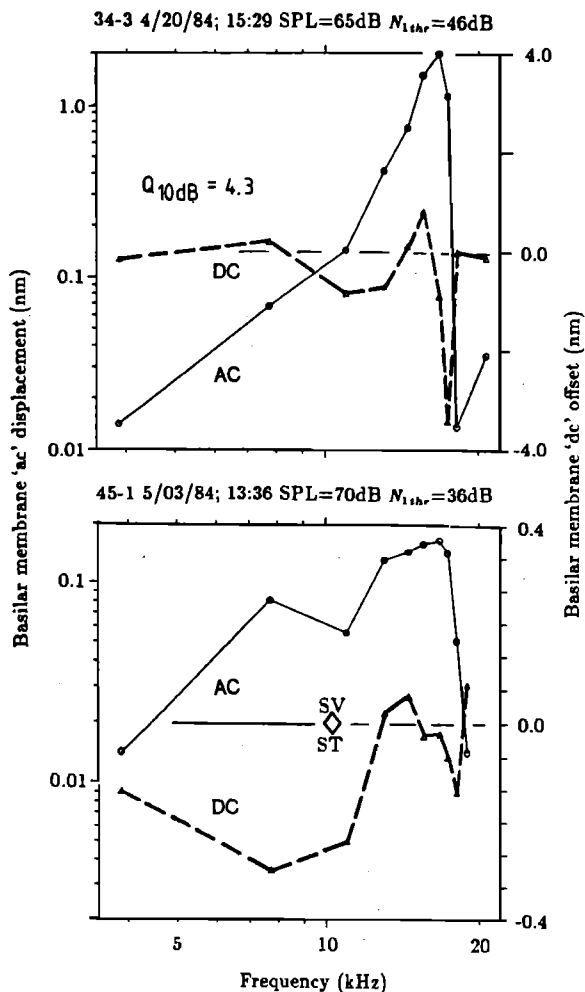45-1 5/03/84; 13:36 SPL=70dB N_{1thr}=36dB

AC

SV
♢
ST

DC

Frequency (kHz)

FIG. 2. Tuning curves from two guinea pigs, showing both vibratory and offset displacement dependence on frequency, for a place about 3.8 mm along the basal turn with an expected characteristic frequency of 15.6 kHz. Two conditions are shown: one in which sharp tuning is evident and one in which the peak is flattened. Later analysis suggests that for the iso-SPL response, the upper, highly tuned ac curve is pathological, which is consistent with its higher N_1 threshold of 46 dB. The flattened peak in the lower curve represents the action of an intact nonlinear compressive mechanism. The dashed curve in each panel represents the corresponding (simultaneous) offsets of the basilar membrane in response to the tone bursts. The displacement in each case is slightly toward SV at the CF. On each side of the CF the basilar membrane is displaced toward ST. Abcissas are the logarithm of frequency (kHz), while the vibratory response is plotted as the logarithm of the probe output (μV). The dc displacements are plotted against the right-hand ordinate in linear μV. Here, dc/ac ratios are mostly less than 1, except for large displacements toward ST. The △ is the baseline dc offset, while the ○ is the fundamental ac component.

II. RESULTS

A. Basilar membrane waveforms

The shift in basilar membrane position is observed in Fig. 1 as an asymmetry of the response to tones at 55 dB SPL about the baseline between bursts. The top panel shows a negative-going displacement offset [i.e., toward scala tympani (ST)] at 11 kHz while the lower panel, at 16.7 kHz [the characteristic frequency (CF)], shows a positive-going offset [toward scalar vestibuli (SV)]. Calibration shows that for a working distance preset to approximately 2 μm the capacitive probe transduces the vibration of the basilar
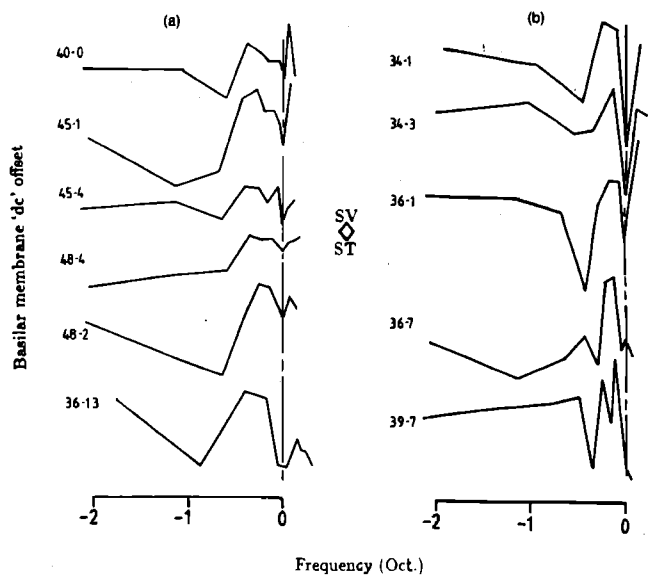

FIG. 3. Patterns of the dc offset representative of the most recent 16 guinea pigs. Despite some variability, the dc offset pattern is clearly trimodal. It is displaced toward SV at the CF, but on either side it is displaced toward ST. The patterns are normalized in frequency by factors which range from 0.0–0.25 oct [panel (a) at bottom], so as to align the high-frequency ST peak of each response. (a) Shows a series in which the patterns are relatively broad. (b) Shows responses more sharply tuned toward SV at the CF, together with a narrower peak toward ST on the low-frequency side. The abcissas are aligned with respect to the high-frequency peak toward ST.

membrane linearly at 500 μV/nm so that these offsets represent average shifts of the basilar membrane of the order of 0.1–0.2nm.

B. Iso-SPL mechanical tuning characteristics: "ac" and "dc" offset responses

Figure 2 shows tuning characteristics for both the vibratory and the offset pedestal of the basilar membrane in examples from two animals. The ac tuning is represented by the solid lines. The top panel in particular shows an example of sharp tuning. The lower panel shows a more typical result in which the amplitudes are smaller, the top of the tuning peak is flattened, and there is a notch approximately one half-octave below the tuning peak. The tuning curve in the upper panel was associated with a drained N_1 threshold of 46 dB, while the threshold in the lower panel was 36 dB. The dashed lines in both panels of Fig. 2 show the basilar membrane offset during the tone burst relative to the baseline before the response.

In each panel, there is a displacement offset toward ST for frequencies less than one half-octave below the CF. As the frequency is increased, there is a tendency for a rapid reversal of direction to positive dc displacement values. This tendency for a displacement offset toward SV is maximal close to the CF. At higher frequencies than the CF, the basilar membrane exhibits an offset toward ST during the burst. This second region of displacement toward ST is narrower in terms of frequency band than the region below the CF and appears to be aligned with the high-frequency slope of the vibratory tuning curve. This "*trimodal*" polarity pattern is observed again in the lower panel, but the vibratory tuning
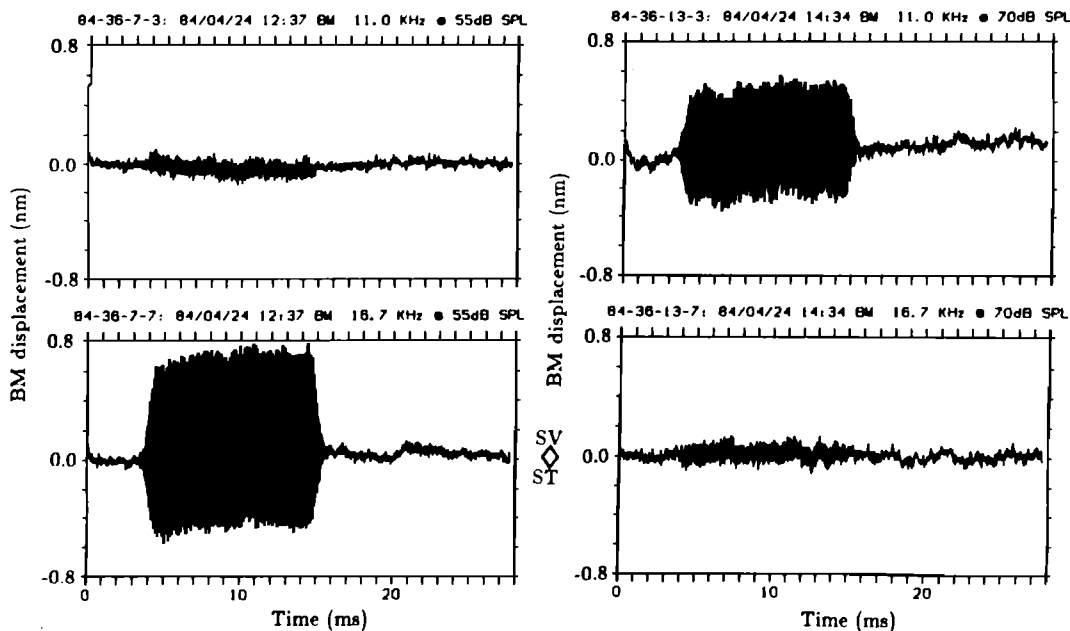
FIG. 4. Demonstration of the decrease in the frequency of both the maximal ac response and the corresponding response in the dc offset toward ST. For a fresh preparation, the two left panels are plotted against time in milliseconds. The two right panels show the response about 2 h later. The top two panels represent the responses at 11 kHz, while the lower two panels represent the responses at the original CF, 16.7 kHz. Both the larger response patterns show slightly positive asymmetry, while the two smaller responses, below CF and above the BF, respectively, show slight negative asymmetries (toward ST).

pattern is more typical in that it exhibits less sharp tuning. In both panels there appears a tendency, at still higher frequencies, for the ST lobe on the high-frequency side to return to the unstimulated baseline, which is represented by the horizontal dashed line.

C. Repeatability of trimodal "dc offset" pattern

There is variability between individual records, yet a trimodal pattern of polarity reversal with increase in stimulus frequency is recognizable across the series of the animals. The three lobes are marked by transitions from an "ST-shift" response to a "SV-shift" response in the half-octave below CF and a transition in the reverse direction above CF in line with the high-frequency cutoff in the ac response. The variability is primarily due to changes in magnitude and bandwidth of the three lobes, yet the ST-shift peak at the higher frequency is consistently the narrowest of the three peaks. The amplitude of the peak toward SV at the CF seems to be small relative to the variable amplitudes of the ST-shift peaks. Figure 3 shows the reproducibility of the pattern of dc displacement as a function of frequency. In the left panel [Fig. 3(a)], the dc tuning curves are broader, while on the right [Fig. 3(b)], a selection of more sharply tuned examples are presented. Although no normalization is necessary to observe the trimodal pattern, the best demonstration of reproducibility is obtained by aligning the ST-shift peak at the higher frequency. The abcissas are therefore shown as octaves less than the frequency of this peak. The normalization factors are small, as can be gauged by the relative horizontal offsets of the left-hand end of each trace. An example of a very late data collection run is included as the bottom trace in the first panel. This was taken from the 13th trial in an experiment after the N_1 threshold had risen to above 60

dB SPL. Since the best frequency had decreased by nearly one half-octave, it is broader than the rest in the series and required a greater normalization factor (1/4 oct) to bring it into line.

D. Shifts in best frequency: "ac" and "dc" offset

Several investigators have documented decreases in the best frequency of the ac response (BF) with deterioration of the preparation (Rhode, 1971, 1973; LePage and Johnstone, 1980; Sellick et al., 1982). It is of interest whether the dc pattern mimics the frequency shift in the ac tuning pattern since this would establish a stronger connection between the observed dc response with the presence of the traveling wave. Figure 4 is for one animal and contains four panels of time data illustrating the shift in BF from 16.7 to 11.0 kHz. Earlier time records in the left panels are compared with later records shown in the two right panels. The top panels are obtained for 11-kHz tone bursts, while the lower panels are obtained for tonebursts at 16.7 kHz. They also illustrate that with the decrease in BF, the basilar membrane displacement response with the slight positive asymmetry also moves with the maximal or BF response. Negative net values are exhibited slightly below the BF in the left panels and also above the BF in the right panels, and are significant after the numerical averaging across the burst response.

The complete frequency picture of the decrease in BF in both vibratory and offset components is shown in Fig. 5. The top panel [Fig. 5(a)] shows two ac tuning curves taken from the same fresh preparation and again 2 h later [Fig. 5(b)] after the preparation had deteriorated. There is an apparent loss of sharp tuning and movement of the BF from the expected CF to a BF of about 12 kHz. Figure 5(c) shows the dependence of the best frequency upon the age of the prep-
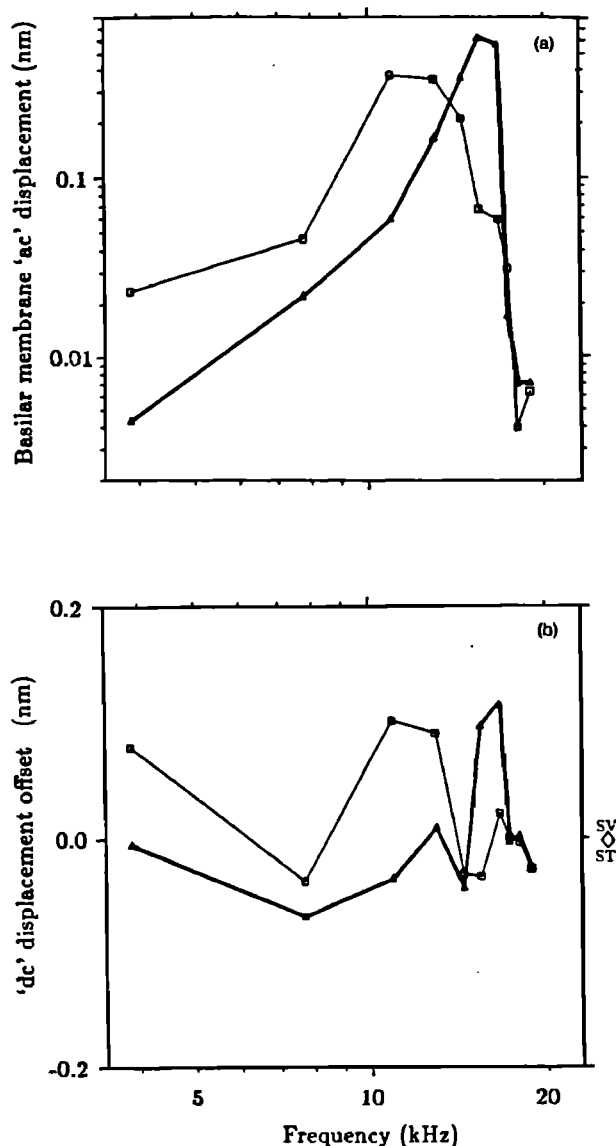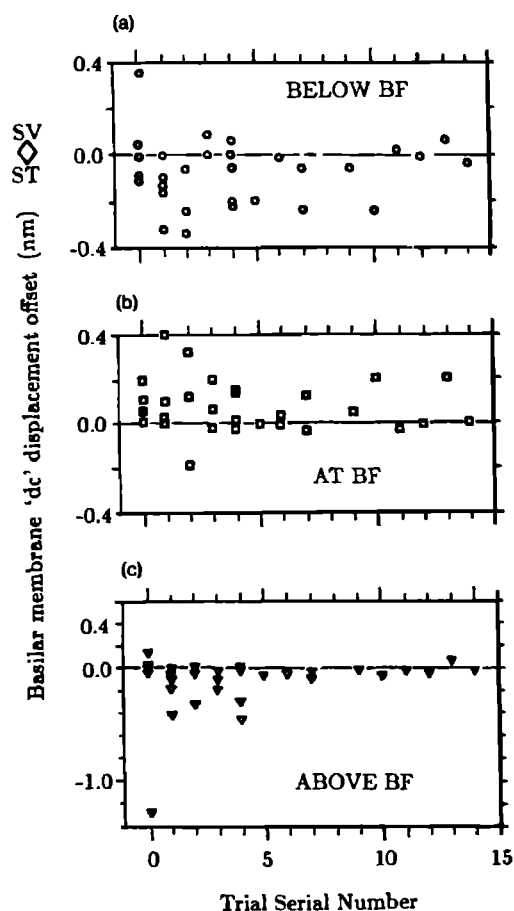
FIG. 6. The three panels represent the pooled results of the 16 most recent animals in the series. Each panel represents a set octave separation from the current best frequency as determined from the ac tuned response. (a) Shows the basilar membrane dc response one-quarter of an octave below the BF, (b) is at the BF, and (c) is one-quarter of an octave above BF. The data suggest that the trimodal dc displacement offset pattern is tied to the traveling wave envelope and that at the BF, the offset is primarily toward SV, while above and below the BF the displacement is primarily toward ST.

aration plotted as the number of the data collection run. It represents pooled data from 27 runs from the 16 most recent animals ($\rho = 0.73$). Figure 5(b) shows the influence upon the offset displacement pattern of decrease in the CF with loss of animal condition. The heavy line corresponds to the case of sharper tuning in the top panel. Together with Fig. 4, these data suggest that at the best frequency of the vibratory response, there is a positive offset toward SV.

E. Trimodal pattern of baseline asymmetry

Figure 6 shows the pooled results of all the animals presented in the three panels as the mean displacement offset of the basilar membrane for each of the frequency regions of the trimodal pattern plotted against the number of the data collection run. In each case, BF represents the frequency of the maximal ac response; this allows for a variation from the estimated CF for the place measured to one quarter-octave below, as shown in Fig. 5. The top panel shows the offset values representing the frequency one half-octave below the BF. There is a trend for fresh preparations to show negative values, representing a net movement of the basilar mem-

FIG. 5. Frequency dependence of the reduction of best frequency below the original CF of 16.7 kHz. (a) Shows iso-SPL ac tuning curves, while (b) shows the corresponding dc displacement picture. ▲ 36-7: 12:37; □ 36-13: 14:34. (c) Shows the reduction in BF as a function of the serial number of the data collection run. The BF decreases with degradation of the preparation. There is an apparent sliding of the whole traveling wave envelope toward the base; this is accompanied by a corresponding sliding of the dc excitation response to SV.
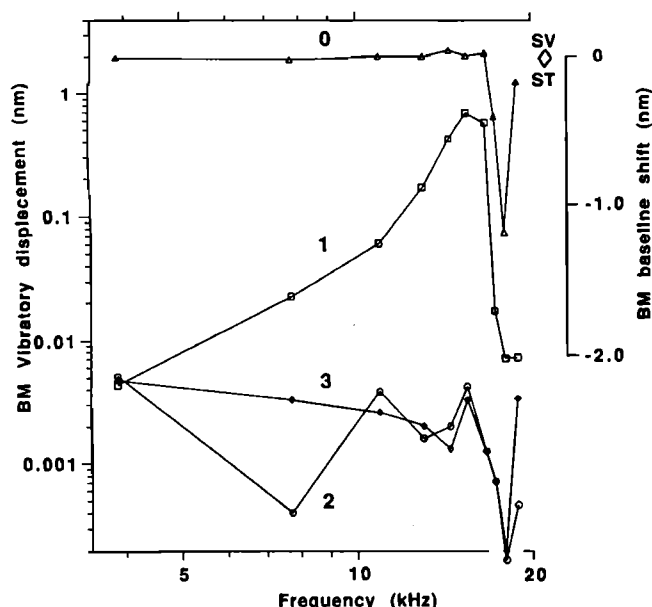
FIG. 7. Frequency variation of the zeroth (0), fundamental (1), second (2), and third (3) harmonics of the ac mechanical response computed for the bins corresponding to the time the burst is on. The noise level is less than 1 pm. For frequencies close to the vibratory peak the harmonic distortion is low, indicating that the baseline shift is not due to a simple rectifying nonlinearity. The same is not true at the lowest frequency of 4 kHz, which shows (coincidentally) similar amplitudes for all. The decrease in the magnitudes of (2) and (3) at the foot of the high-frequency cutoff suggests resonance. Also $\triangle$ is zero frequency (0); $\square$ is fundamental (1); $\bigcirc$ is 2nd harmonic (2), and $\lozenge$ is 3rd harmonic (3).

brane toward ST during the tone burst. The second panel shows the situation for BF values. There is a clear tendency for mostly positive values; this represents movement toward SV. Finally, the bottom panel shows the situation for the pattern 0.3 oct above the BF. Here the values are significantly below the zero line, indicating a movement of the basilar membrane toward ST. In all three panels the largest offsets occur in the first few runs and decrease in magnitude as the preparation ages. The dc components do not disappear completely over this time span, but have not been followed postmortem.

F. The baseline shift toward ST above CF appears to be aligned with a resonance

A dc offset could be due to two effects. First, a dc offset could be due to the existence of significant even harmonic distortion, such as would be the case for a diode-type of nonlinear transfer characteristic. In this case, one might expect to observe significant even harmonic distortion in the tonal response. Alternately, the origin of the dc offset could be due to a second process dependent upon the presence of vibration, but not intimately coupled to it, so that only a pedestal may be observable without any distortion. Figure 7 shows an example of determining the second and third harmonics of the response during the tone burst plotted with the fundamental, which is moderately sharply tuned. Notably, at the best frequency of the mechanical response, the second and third harmonics are 45 dB below the response of the fundamental. This shows that the dc pedestal exists independent of harmonic distortion in the waveform. The same is not true of

the result at the lowest frequency (4 kHz), suggesting that the low-frequency response to a tone may be accompanied by significant distortion.

The most striking feature of these data, however, is the reduction in the second and third harmonics as the frequency approaches the foot of the high-frequency cutoff, the frequency at which, according to traditional traveling wave theory, the mechanical response changes from being stiffness to mass dominated. At this frequency the reactance terms cancel; this constitutes resonance, the appearance of which will strongly be affected by the value of the damping. In Fig. 7, the reduction in second and third harmonic data is therefore consistent with a mechanical resonance at this frequency and not at the best frequency. In relation to the traveling wave envelope this frequency is located at the apical end of the envelope, and does not appear as a peak, suggesting that the resonance is not in the transverse plane of the measurement. Moreover, the top trace indicates that the zeroth harmonic (short-term dc component) undergoes a strong shift toward ST at the same frequency, about one-sixth of an octave above the best frequency. The baseline shift at this frequency can be very large, and several examples have been seen where the shift was so large that the fluid covering the basilar membrane actually came into contact with the tip of the capacitive probe, indicating a shift of ca. 1 μm. Such a large shift may be expected to alter the sensitivity of the capacitive probe, however, it is likely to increase it, so the reduction in amplitudes is likely to be underestimated. The resonance therefore appears marked indeed.

G. Results are not invalidated by draining procedure

The most readily available indicator of viable cochlear mechanisms is low neural thresholds. Figure 8 shows the N_1 threshold plotted versus the number of the data collection trial for the same 27 records. Draining of scala tympani will have the effect of increasing the electrical resistance in ST and hence a higher sound level may be required to detect an
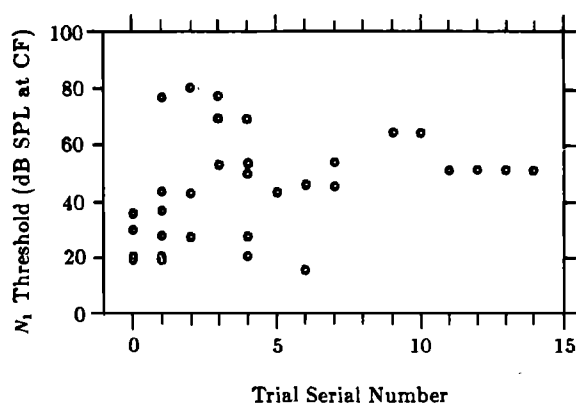

FIG. 8. The N_1 threshold, measured in the drained condition, plotted against the serial number of the data collection run for the same 27 trials. The basilar membrane displacement data were taken from a significant number of records in which the sensitivity of the cochlea was not severely compromised. There are 12 records with thresholds lower than 40 dB SPL.

N_1 response. Hence, thresholds obtained in the drained condition are likely to be overestimated rather than underestimated. The results of this figure, however, show that a substantial number of records from which these data are taken are obtained in a low threshold condition, demonstrating that draining scala tympani does not always produce high thresholds. Indeed, there are six cases with thresholds of 25 dB SPL or less. Due to the effects of draining scala tympani, high thresholds often result; this situation is probably analogous to the rise in the threshold of single spiral ganglion cells described by Robertson (1974). The figure shows, however, that draining does not always produce loss of sensitivity, suggesting that some additional factor is involved. The scatter plot also shows that aging of the preparation invariably occasions a rise in threshold to values of 50 dB SPL and above.

H. Completing the "dc" picture: Net displacement of the mean position of the basilar membrane measured over a longer term

Figure 9 shows more completely the interrelationship which appears to exist between the vibratory and dc components of basilar membrane motion for three records from the series with low N_1 thresholds. For the isoresponse contour-tracking procedures common to threshold tuning curves, sharp tuning would be expected for the low thresholds recorded for these curves. On the other hand, the three ac tuning curves of Fig. 9(a) are obtained for a constant sound-pressure level of 70 dB SPL. In many of these data, the null below the ac peak may be pronounced. This causes the tuning curve to display evidence of tuning, but despite the low thresholds, the tuning curves overall show tip-to-tail ratios of less than 40 dB. The curve represented by the triangles applies for the lowest threshold of 19 dB, whereas the curve represented by the circles applies for a threshold of 27 dB. The curve which applies for a threshold of 36 dB (squares) also shows a greater tip-to-tail ratio consistent with less compression. Again, the maximum displacements represented by these curves are 0.2 nm, being similar to threshold displacements previously registered by Sellick *et al.* (1982).

The dc picture corresponding to these curves is shown in Fig. 9(b) and (c). The values of the offset pedestal are shown in Fig. 9(b). The curve represented by the triangles correlates with the ac curve with the least peaking at the CF and is the most constant in its dc response. The curve with the squares exhibits a ST component 1 oct below the CF and like the triangles, a return toward SV and small dc values at CF. In the curve with the circles a clear trimodal pattern is evident, with the greatest SV asymmetry at about the best frequency.

Figure 9(c) is a measure of the change in the long-term absolute position of the basilar membrane as a function of frequency. Each point is the result of determining the mean value of the unstimulated baseline, from which is subtracted a reference value for the trial at the lowest frequency. All three preparations therefore register zero for the lowest frequency.
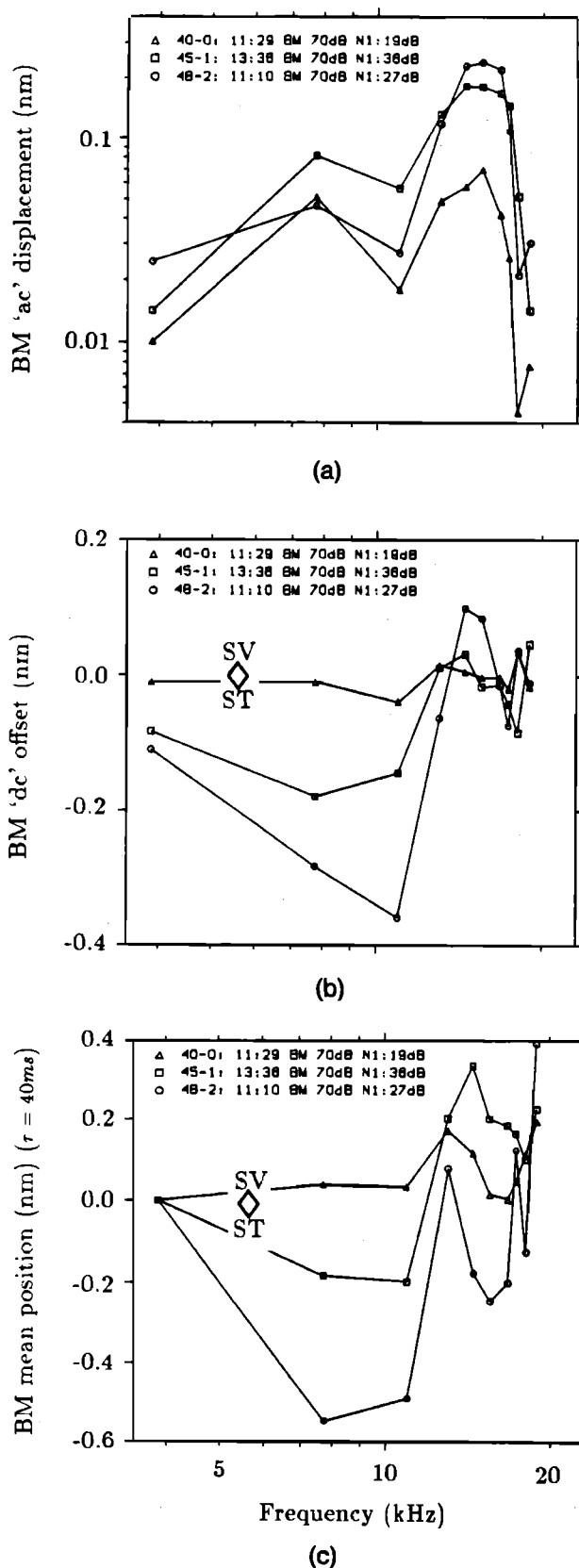

(a)

(b)

(c)

Frequency (kHz)

FIG. 9. Examples of each of the components of the motion from three animals with low to medium thresholds as determined by the N_1 threshold in the drained condition. Panels (a), (b), and (c), respectively, represent the frequency response characteristics of the basilar membrane for the ac response, the dc offset response averaged over the tone burst, and the accumulated incremental change of the overall mean position of the basilar membrane over the total averaging time per trial. Also, in (a), (b), and (c), △ 40-0: 11:29 BM 70 dB N_1:19 dB; □ 45-1: 13:36 BM 70 dB N_1:36 dB; ○ 48-2: 11:10 BM 70 dB N_1:27 dB.

The signal from the capacitive probe was ac coupled with a time constant of 40 ms. This means that if the mean position of the basilar membrane remained unchanged for the 10-s period of averaging, the baseline change would be zero across all trials. Even if the basilar membrane position changed at the beginning of each new frequency and then remained in a fixed position, the signal being averaged would have decayed to zero in the first 100 ms and no significant change would have been registered in the average. The fact that there does appear to be a systematic change in the average indicates that each tone burst triggered an incremental change in the mean position of the basilar membrane, which although differentiated by the amplifier, has been summed over the 10-s period of averaging. The magnitude and polarity of this change follows a similar pattern, which is strongly related to the short-term pedestal response obtained well within the repetition period.

These data therefore give only a limited view of the time course of the change in mean position of the basilar membrane over the 10-s averaging period. Nevertheless, there is much useful information contained in Fig. 9(c). The summated values are generally larger than the dc pedestal values in Fig. 9(b). At the CF, there is an overall movement of the basilar membrane which accumulates toward ST. Over the 10-s period of averaging, there were some 288 bursts delivered. For the curve represented by the circles, a significant shift must have accumulated toward ST between the 3.8- and 7.7-kHz trials, amounting to 0.55 nm×288 = 150 nm. As the frequency was raised between 11 at 13 kHz, entering a region within one half-octave of the CF, there is a rapid swing toward SV of more than 150 nm, while further position changes must have occurred at the CF and the high-frequency cutoff, accumulating to 100 nm. This constitutes a lower bound on the accumulated shifts. It is not possible to say on the basis of these preliminary measurements of the long-term movement what the upperbound of the shift might be, but it can be said that this summated movement cannot be simply attributed to electrical and mechanical drifts. These movements must be occurring with an average velocity of about 10–15 nm/s. This velocity is therefore between one and two orders of magnitude larger than the 0.3 nm/s effective dc drift in the measurement system after 45 min stabilization, (LePage, 1987a). Moreover, these summated shifts exhibit changing polarity at frequencies meaningful for the tuning process, whereas over a period of many minutes, electronic drift in the measurement system is generally monotonic. There is a good deal of variability which may be attributable to longer term drifts and other forms of noise, but the overall pattern appears similar across experiments carried out over a 2 month period.

I. Opposite directions of the short- and long-term "dc" components at CF

For frequencies about 1 oct below the CF, Fig. 9(b) again shows that the mechanical response of the basilar membrane to a tone burst exhibits an asymmetry toward ST. Figure 9(c) shows that in addition, the mean position at this frequency has also moved strongly toward ST. As the fre-
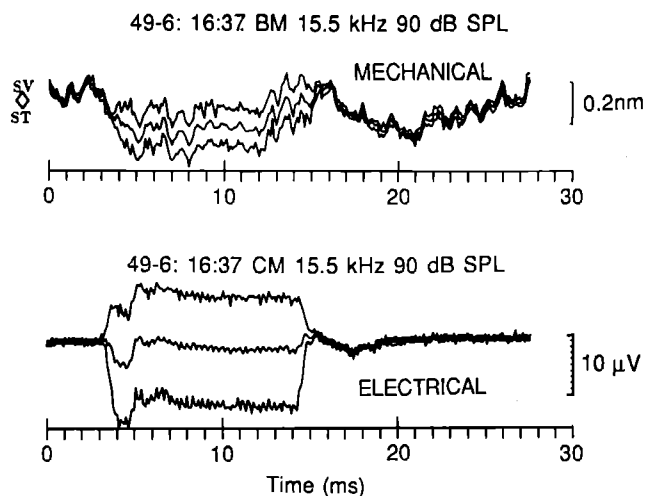
quency is raised above the point one half-octave below the CF, the offset asymmetry is toward SV, and so is the mean displacement of the baseline. As the frequency reaches the CF, however, the offset is toward SV, but this appears to be accompanied by a pronounced movement of the baseline back toward ST. Above CF the offset asymmetry reverses toward ST again and the position of the baseline appears to swing again toward SV. These patterns vary in magnitude across the three animals, but, overall the offset displacement and baseline displacement patterns are preserved.

The important point is that within the half-octave region associated with "active" behavior, there is a differential effect in the two displacements. *This suggests that for every fast movement toward SV, there is a slow sagging movement of the baseline toward ST in the active region.* An octave below CF both the asymmetry and the baseline shift tend to be toward ST, but, at CF the asymmetry and the mean position of the basilar membrane are in opposite directions. Furthermore, there is tuning in both the short- and long-term measures of the low-frequency mechanical response.

J. Response to a high-intensity tone

The usefulness of the round window potential recordings is twofold. They were necessary for determining the N_1 threshold; hence the round window signal was high-pass filtered with a break point at 60 Hz and low-pass filtered at 600 Hz.[2] The potential measurements are also useful as a simple means of simultaneous measurement of the summating potential (SP) within 2mm of the location of the capacitive probe tip. The resulting records therefore are a combination of the compound action potential (CAP) plus an ac-coupled signal proportional to the SP.

Figure 10 shows an example of simultaneously measured mechanical and electrical responses for a 90-dB SPL tone burst, an experiment similar to the experiment of Cody and Russell (1985), although the latter did not include any measure of mechanical response. For clarity, in each panel, the upper and lower traces represent the envelope of the response, while the central line represents a moving mean value. In each case the values plotted are computed over one cycle of the tone. The upper panel shows that the basilar membrane displacement asymmetry toward ST exceeds the vibratory component. The result is consistent with Russell's interpretation (1985) that the depolarization, which Cody and Russell associate with temporary threshold shift (TTS), is accompanied by an evoked mechanical shift toward ST of about 0.2 nm.

K. Frequency dependence of mechanical and electrical responses

In Fig. 11 plots of the frequency dependence of both the mechanical and electrical behavior, measured concurrently at 65 dB SPL, are presented. The top panel represents the mechanical response, with the continuous line (circles) representing the tuned vibratory response. The dashed lines represent the measures of steady displacement. Again the triangles represent the average baseline shift during the tone burst relative to the preburst baseline, while the squares represent the long-term movement of the basilar membrane determined prior to each tone burst. The lower panel represents the corresponding electrical picture obtained on the second channel. The continuous line here represents the CAP amplitude (i.e., the difference between the P_1 and N_1 peaks after filtering out the cochlear microphonic), while the dashed lines represent similar measures of the dc electrical behavior. The triangles represent the initial dc swing of the SP (the asymmetry in the CAP at the beginning of the tone burst), while the squares represent the residual shift (after filtering) in the electrical baseline. Hence, the short- and long-term measures of the summating potential from the round window are determined using the same subroutine and appear to mimic the short- and long-term measures of the mechanical baseline shift.

In the drained condition, the SP is expected to be a weighted sum of the responses of the receptors in the vicinity of the round window (ca. 2.5 ± 2 mm from the stapes) and, therefore, to be a fair representation of the receptors in the region of the capacitive probe tip. The baseline displacement is much more sharply tuned than the SP measured at the round window. This may be because the spatial resolution of the capacitive probe is about ± 50 μm, (1/25 oct), maximum (LePage, 1987a). The dc mechanical responses appear to be well correlated with the measures of the SP, which show the positive-going response at the CF expected for an electrode located in ST. At the same time, the basilar membrane response is an offset toward SV. The peaks in both mechanical and electrical dc responses appear to be shifted in frequency one-sixth of an octave above the best frequency of the vibratory response and of the CAP. Indeed, there is a remarkable similarity between the long-term value (squares) and the differential (or DIF) component of the SP (Dallos et al., 1972).
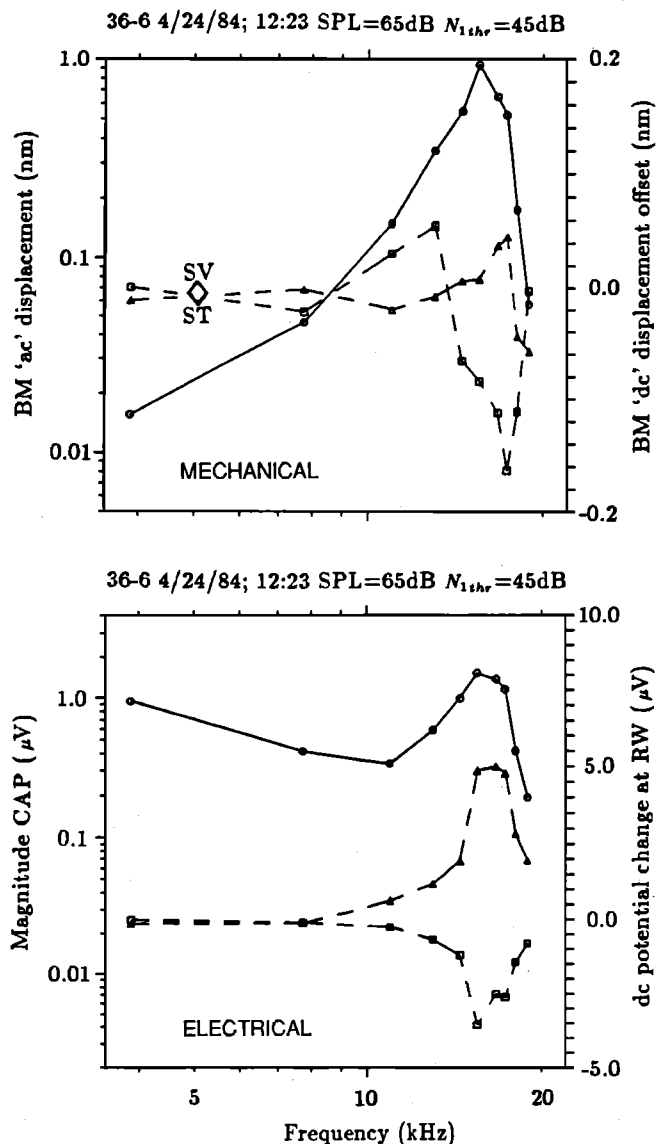

FIG. 11. Simultaneous mechanical (top panel) and electrical (bottom panel) frequency response functions for a case of medium threshold sensitivity (45 dB SPL). The upper panel shows vibratory and offset response amplitudes plotted on log and linear ordinates, respectively, and takes into account the displacement calibration factor of 2 nm/mV. The electrical picture in the lower panel is derived from the peak-to-peak response of the CAP (circles), the magnitude of the initial electric dc offset pedestal in response to the tone burst (triangles), and the residual electrical baseline variation reflected in the average position during the preburst interval. There is a clear correlation between the mechanical and the dc offsets close to the best frequency. The sharper tuning in the mechanical dc component reflects the much higher spatial resolution of the mechanical recording. Upper panel: O is the ac component: fundamental; $\triangle$ is the displacement offset during burst, and $\square$ is the baseline value before burst. Lower panel: O is the magnitude of CAP, $\triangle$ is the baseline offset during burst; and $\square$ is the baseline value before burst.

III. SUMMARY OF RESULTS

(1) Basilar membrane mechanical data obtained from low threshold cochleas in fresh guinea pig preparations reveal a steady displacement in addition to the traveling wave. Its temporal properties appear to be very different from those of the traveling wave.

(2) Draining of ST does not necessarily produce a marked loss of cochlear sensitivity. The loss of sensitivity observed in this and earlier investigations appears to be dependent on some additional factor.

(3) The vibratory responses vary from 0.2–2 nm. For recordings from preparations with N_1 thresholds of 20 dB or less, the vibratory component of the motion to a 70-dB SPL tone appears to be of the same order of magnitude as the displacements at threshold measured by Sellick et al. (1982).

(4) The vibratory component may appear much more sharply tuned than previously seen with the capacitive probe technique. Mostly, however, the records taken at lower thresholds show lower magnitudes and tip-to-tail ratios, but because of a null in the vibratory response about one half-octave below the CF, tuning may be apparent despite comparable magnitudes of the tip and tail.

(5) The dc displacement component appears to be separable into two distinct parts. The first is a response to low-level gated tone bursts that is asymmetric with respect to the baseline. The magnitude is ca. 0.2 nm *per burst*. The ratios of the displacement to vibratory components are small except at frequencies much less than the CF. The offset in response to a high-level CF tone burst may be much larger than the small values measured at lower levels.

(6) The second component of the displacement indicates an accumulation of a progressive shift of the basilar membrane from its original position with each tone burst and may accumulate to shifts of fractions of a micrometer. Estimations of the average velocity in the region of the CF may be at least 10 nm/s at 65 dB SPL.

(7) Both the short-term offset and the long-term position shift appear to exhibit the same direction 1 oct below CF and opposite directions in the region of the CF, with the short-term toward SV and the long-term toward ST.

(8) The frequency dependence of the short-term offset appears to be trimodal, with displacements toward ST above and below CF, but with a tendency to displacement toward SV at the CF. The rapid transitions in the basilar membrane position tend to be aligned in frequency, with rapid changes in the magnitude of the vibratory response.

(9) The long-term mean position of the basilar membrane also varies systematically with frequency and the displacement appears to be tuned to a frequency which is just above the best frequency of the vibratory response. The amplitude of the vibration tends to be reduced in regions where the basilar membrane is displaced toward ST.

(10) The short-term component does not necessarily disappear with degradation of the condition of the preparation. Instead, as the best frequency of the vibratory response decreases and the curve broadens, the displacement appears to follow the same pattern and broaden.

(11) There appears to be a resonance in the mechanical response at the foot of the high-frequency slope about one-sixth of an octave above the best frequency, i.e., spatially, at the apical end of the traveling wave envelope. This is associated with a null in the second and third harmonics and often a large baseline swing.

(12) The pattern of the long-term baseline shift is very similar to that of the DIF component of the summating potential, with the maximum displacement toward ST coinciding with the negative peak in the SP, both at about one-sixth of an octave above the CF.

IV. DISCUSSION

The results of this study include what are believed to be the first direct measurements of waveforms of the basilar membrane motion in response to gated tone bursts, made possible through the high displacement sensitivity, speed, and wide linear range of the capacitive probe technique. These data suggest that in fresh guinea pig preparations with low hearing thresholds, the basilar membrane motion is not completely described by an "ac" traveling wave. Instead, the complete description should include specification of the behavior of the mean position of the basilar membrane since this exhibits systematic short- and long-term changes as a function of frequency. Moreover, the size of the "long-term" baseline change may be quite large, much larger, in fact, than the vibratory component. This finding immediately overcomes the largest single obstacle to progress in understanding cochlear mechanisms, namely, that the motions of the basilar membrane at threshold are so small as to be undetectable by the inner hair cells. Further, the finding is more consistent with the purported existence of a cochlear amplifier (Davis, 1983), whose output at high frequencies is a "dc" component.

A. Effect on threshold of draining scala tympani for the measurement

A major area of concern is that draining produces a significant threshold loss (Robertson, 1974). It has been demonstrated here, however, that while significant losses may occur, many records in the drained condition have been obtained with small threshold losses. Since thresholds raised by 30 dB were the major complaint with earlier uses of the capacitive probe, the low thresholds obtained in this study are regarded as a sufficient indicator that the (active?) mechanism responsible for the basilar membrane nonlinear behavior is functioning.

There has been some discussion (Khanna and Leonard, 1986a) concerning damage to the cochlea occasioned by invasive measurements. The most important of the measurements reported here did not require significant preparation time; they were completed within 90 min of anesthetizing the guinea pig. Low hearing thresholds were certainly not always achieved or maintained. However, the prime object of the study was to characterize active or electromechanical activity as a class of behavior discernable from the passive traveling wave. It was shown earlier (LePage, 1981) that, while neural threshold response remains below 65–70 dB SPL, some nonlinear compression is evident with the technique employed here.

B. Trimodal baseline shift

The pattern of asymmetry of basilar membrane displacement responses to tone bursts appears to be trimodal and is repeatable across the series of animals studied. Frequencies less than one half-octave below the CF are now associated with a burst response asymmetry toward ST, plus a larger net accumulating shift or mean velocity also toward ST. Frequencies around CF at which compressive behavior was previously seen in the ac response (LePage, 1981) are now associated with a burst dc offset in the direction of SV

and mean basilar membrane velocity toward ST. Frequencies $\frac{1}{4}$ oct above CF in the plateau region, and previously associated with expansive behavior, are now associated with burst offset toward ST and velocity toward SV.

C. Influence of accumulating "dc" component on capacitive probe sensitivity

An important issue concerns the existence of the dc shift and its effect upon capacitive probe sensitivity. The shape of the ac tuning curves obtained will be, in part, due to changes in sensitivity of the probe with changes in position of the basilar membrane. As shown elsewhere (LePage, 1987a), at a working distance of ca. $2 \mu m$, the calibration of the capacitive probe does not change by more than 6 dB for a 1-μm absolute change in probe-to-basilar membrane separation. This means first, that sensitivity variations due to respiration movement (ca. 25 nm) can be disregarded. However, accumulated dc displacements of the basilar membrane may influence the capacitive probe sensitivity and the apparent ac amplitude if the basilar membrane approaches the tip of the probe more closely still. It seems from the present study that the size of the long-term displacement is ca. 150 nm, but also that this figure could be underestimated. In the instances where the size of the baseline shift may have been more than $1 \mu m$, this will have increased the capacitive probe sensitivity, and so the vibratory magnitude will have been overestimated.

The problem of the measurement technique being influenced by large basilar membrane movements is not limited to the capacitive probe. By comparison, large movements could substantially influence the ease with which a laser interferometer (Khanna and Leonard, 1986a,b) could measure basilar membrane vibration. The velocity of the basilar membrane toward ST at the CF apparently does create beam alignment problems the moment sound is delivered to the animal (Khanna, 1983). It may be possible to obtain stable tuning curves only after the animal condition has deteriorated and the long-term baseline variation has diminished.

D. Correlation between basilar membrane position and vibratory amplitude

The most significant feature of Fig. 9 is the correlation which appears to exist between the magnitude of the ac component and the short-term position of basilar membrane. Shift of the basilar membrane toward ST appears to be associated with smaller vibratory amplitudes. The large mean shift of the basilar membrane for frequencies less than 12 kHz are associated with small amplitudes of the ac response in this region, as expected from previous studies. As the frequency increases above 11 kHz (one half-octave below BF) the abrupt swing of the mean position of the basilar membrane toward SV is associated with a rapid increase in the ac component. Likewise, as the frequency passes the CF, the SV shift is rapidly replaced by a second ST shift which can be very marked, coincident with the high-frequency cutoff and signs of resonance.

At first glance these data suggest that the nonlinear mechanism gives rise to a larger dc component with larger ac amplitude, suggesting the involvement of a rectifier located after the macromechanics which, for a larger ac component, produces a larger dc value which is coupled back to the basilar membrane. Figure 7 offers some light on this possibility. The ac component shows little sign of harmonic distortion which would characterize a passive, diode type of rectifier. The figure suggests that if such rectification occurs, it is not evident in the motion of the basilar membrane at high frequencies, but may be for frequencies 4 kHz and below.

The preferred interpretation of these data is that the dc component is generated peripheral to the OHC (LePage, 1981) and that, in response to this dc component, the OHC controls the vibratory magnitude, e.g., under the control of the dc component, the OHCs control *damping* of the vibratory response. Damping is decreased at the CF in proportion to the short-term baseline shift toward SV and is greatly increased for frequencies on either side of CF.

E. Role for the accumulating displacement shift

The mean position of the basilar membrane changes with change in frequency during normal acoustic stimulation. This suggests adjustment of the mean position or an adaptation to each new stimulus, which constitutes a "self-induced" bias in the position of the basilar membrane. The importance of such a self-induced bias may be estimated from known effects of biases artificially applied to the basilar membrane. Other studies have shown that the single neuron sensitivity and also the sensitivity of the basilar membrane may be modulated by low-frequency acoustic tones which cause small bias displacements (LePage, 1981; Schmiedt, 1982; Patuzzi et al., 1984b,c). These low-frequency tones produced net displacements of the basilar membrane alternately toward ST and then toward SV. The first of these studies showed that a bias of 10 nm in the position of the basilar membrane may modulate the sensitivity of single units by as much as 40 dB. The data shown in Fig. 9 suggest, however, that under the circumstances of the measurement, shifts may have accrued to as much as 150 nm. In other words, the self-induced bias is at least comparable in magnitude and possibly even larger than net artificially introduced biases that effect substantial changes in cochlear sensitivity.

The importance of the frequency dependence of the "self-induced" bias is that it will produce vibratory sensitivity of the basilar membrane, which is also frequency dependent. Therefore, it seems highly probable that the self-induced biases control or modify the shape of the tuning curve. The shape of the ac tuning curve at normal sensitivity may be under tight control of the absolute transverse position of the basilar membrane. *The data are internally consistent with the interpretation that the nonlinear compression or expansion, apparent in the ac response, is really a manifestation of this much more fundamental form of displacement control upon the local mechanical properties of the basilar membrane.*

F. Consistency tests

If control of sensitivity by self-induced bias really exists, then certain features of the data must be consistent, e.g., the frequencies of peaks in the dc offset response should be aligned with the frequencies of maximal compression and expansion. Second, the frequency of the peak of the long-

term component should correspond with the frequency of greatest modulation of the sensitivity of the neural tuning curve.

Indeed, both requirements appear to be met. Earlier studies showed that the nonlinear compression is "tuned" to a frequency about 1/7 oct above the CF and extends by about 0.6 oct to lower frequencies; this finding is consistent with Rhode's data (Rhode, 1978; LePage, 1981). Looking again at Figs. 9 and 11, a characteristic feature of the long-term shift is the large swing of the basilar membrane toward ST just above the BF. In Fig. 9(c) the values are greatest between the BF and about 1/5 oct above it. The actual shape of that peak is quite reproducible (see, also, Fig. 11) and a small increase in frequency causes a sudden increase in the magnitude of the displacement. A salient feature of the earlier study (LePage, 1981) was pronounced nonlinear expansion for frequencies 1/3 oct above the BF, in the "plateau" region. This feature has not been reported elsewhere and appears to have been captured by virtue of the wide dynamic range of the capacitive probe technique. In the current study it appears that the expansion may be attributable to movement of the basilar membrane toward SV, reversing the compressive trend seen at the CF.

In regard to the second requirement, the neural bias study (LePage, 1981) coincidentally finds that the frequency of greatest influence on the neural rate-level functions is maximal at 1/7 oct above the CF, the frequency of highest slopes (Sachs and Abbas, 1974). *If movement toward SV is excitatory for the IHC, then the long-term baseline shift toward ST above the CF would result in a decrease in the slope of the rate-level functions for higher frequencies than the CF* (LePage, 1987b), *and therefore the sharpness of tuning. The shift to lower frequencies in the trimodal pattern seen in Fig. 5 indicates that a similar shift must be seen in the rate-level functions so that they will tend to flatten for a lower frequency.* Following this argument one step further, the large shifts toward ST *below* the CF might be expected to flatten the rate-level curves as well. Perhaps this is an indication of a correlate of hypersensitivity in the tails of neural tuning curves in the capacitive probe preparation?

In several data collection trials (e.g., Fig. 7) a huge peak occurred in the displacement toward ST above the frequency of the maximal ac response. In an earlier series of capacitive probe experiments using continuous tones, a repeated occurrence was the tendency for the air gap to be bridged rapidly by the fluid covering the membrane, short-circuiting the probe oscillator as the best stimulus frequency was approached. Displacements of the basilar membrane could approach 1 μm in the span of 1 s. This would modify the frequency response properties in a way identical to the effects of a loud tone, producing a temporary threshold shift (TTS) (LePage, 1981). These kinds of behavior lead early to a very complex and unstable picture of cochlear mechanics as viewed by this capacitive probe technique (LePage and Johnstone, 1981b). By comparison, the technique of Wilson and Johnstone (1975) allowed for tracking slow baseline movements so that their results did not appear so unstable. It is intriguing that they likewise saw no nonlinear behavior, except at the foot of the tuning curve, where we now see the

rate of baseline shift is maximum. In the same study of continuous pure tones (LePage, 1981), the ac response magnitude of the basilar membrane just above CF remained at a constant value above the noise level, i.e., input/output slopes of 0 (dB/dB) over a 45-dB range of intensities. The inference is that for frequencies close to CF, the magnitude of the ac component may remain nearly constant, and not just for the threshold condition for all sound levels up to 70 dB, as suggested by Sellick *et al.* (1982). If, indeed, the compressive mechanism functions over such a substantial dynamic range, the probability of attributing this kind of behavior to a passive mechanism appears to be reduced.

G. Effect on mass of draining scala tympani for the measurement

Draining may cause a further possible disturbance from normal cochlear function. It may produce a shift in the cutoff frequency due to halving of the effective fluid mass (Steele and Zais, 1985). It is not clear from the present data that a significant shift occurs, since the lowest threshold preparations all show best frequencies close to the guinea pig map established by Wilson and Johnstone (1975) and repeated by Robertson and Johnstone (1979). According to this map, CFs of 15.5 kHz were expected, but frequently BFs of 16.7 kHz were obtained; this may indicate a 0.1-oct shift consistent with the model prediction. It is clear from the foregoing discussion that an unwanted bias of the basilar membrane position due to draining may influence the CF as strongly as variation in fluid mass, so some further controlled experiments are necessary to determine which effect is dominant. For this experiment it may be necessary to use a displacement technique which does not require draining the perilymph, such as a fiber optic lever (Cook and Hamm, 1979).

H. Are we dealing with an automatic gain control (agc) mechanism?

The mechanical data are consistent with the concept of a feedback loop which simultaneously achieves signal compression over a wide dynamic range of possible sound levels, while for any fixed "state" the cochlea transduces small signals linearly. This is essentially the description of an agc mechanism, such as used in radio receivers in which a dc signal is derived from the output of the detector and applied as negative feedback to control the gain of the input stage amplifier before the detector. The analogous situation proposed here is that a dc feedback control signal is derived from the mean position of the basilar membrane.

The behavior of such a sensitivity control mechanism in response to acoustic stimuli may appear highly complex. The behavior of agc systems is determined not just by the components of the system, but also by the nature of the stimulus itself, in this case whether the stimulus is noise or tonal and whether it is continuous or discontinuous. If discontinuous, the temporal nature of the stimulus may be very important since there will be changes in effective sensitivity with the onset and offset of each burst which will appear as adaptation in the overall response. A second characteristic of agc systems is that if dc conditions stabilize, the system will appear to transduce the small ac signals linearly. Such

an interpretation would be consistent with reverse correlation studies in which responses of the auditory nerve appear linear (deBoer, 1969; Evans and Wilson, 1973). Otherwise, level-dependent nonlinearities will not only be apparent, but will be difficult to characterize without proof that the ac sensitivity in the feedback loop is a function of the dc conditions at the output of the loop.

I. Two-tone suppression

The results suggest that the mechanical motion of the basilar membrane actually contains the basis for lateral suppression in the cochlea directly, obviating some of the need for Békésy's forearm model (1960, p. 550ff.) to explain perception of spatial contrast. Two-tone suppression (Sachs and Kiang, 1968) could be a specialized case of a basilar membrane bias, where the change in the dc stimulus to the IHCs at some place along the cochlear partition is produced by competition for sensitivity control between two dc offsets resulting from two tones (LePage, 1981). Indeed, there are similarities between the trimodal displacement patterns of Fig. 3 and two-tone suppression contours (Legouix *et al.*, 1973; Sellick and Russell, 1979; Jesteadt and Norton, 1985). Kim (1986) has also recently suggested that part of the two-tone suppression response may be attributable to a dc component of the motion of the cochlear partition.

J. Summary

In terms of the experimental design objectives expressed by LePage (1987a), these data are preliminary only. However, it would appear that the basilar membrane baseline displacements may be evidence of a graded OHC electromechanical response which results in a self-induced bias. If so, the mean position of the basilar membrane is itself a highly controlled parameter of cochlear function. Moreover, it may be modified in temporary threshold shift and disturbed in conditions such as endolymphatic hydrops.

The apparent dependence of the magnitude of the vibratory magnitude on the amplitude and polarity of the self-induced bias suggests that a motile response may have an important role in establishing nonlinear compression in the mechanical response, and thereby on the threshold sensitivity in the neural tuning curve. These findings need more detailed study; however, they are more consistent with a hypothesis of sensitivity control than any other data so far advanced. This is because these data have been obtained by localized, direct mechanical measurement and are not inferred from more remote acoustic, electrical, or neural responses. The critical additional information required has been the low-frequency behavior of the basilar membrane in response to a high-frequency stimulus. Most measures of cochlear function so far available appear to have been high-pass filtered for one reason or another, either by internal filtering of the receptor cells or external filtering by the means of transduction. The present mechanical data have also been high-pass filtered (corner frequency 4 Hz), but they contain a measure of the displacement during the setting of the steady position of the basilar membrane. This measure is consistent across preparations in the series.

The results strongly suggest more than one mode of motion of the basilar membrane. There is the traveling wave, or vibratory component; a baseline variation which is near instantaneous with the onset of an acoustic stimulus; plus a longer-term change in the mean position which appears to be an analog of the summating potential. Moreover, the ST shift above CF appears to be associated with a pronounced resonance. However, the resonance does not appear as a peaking in the magnitude of the transverse vibration of the basilar membrane. This suggests that the resonant mode may be elsewhere in the cochlear partition but is coupled to the transverse motion of the basilar membrane. Perhaps it is normal (e.g., longitudinal) to the transverse plane of measurement? This may explain the puzzling, yet potentially most important, contribution by von Békésy (1960, p. 497): the stroboscopic description of the motion of the organ of Corti and tectorial membrane, which describes a longitudinal resonance at the end of the traveling wave pattern for a tone.

The largest single question arising from these data is the origin of the trimodal component of short-term baseline shift. From Fig. 5 it is clearly tied to the action of the traveling wave upon the organ of Corti. The fact that it did not appear to diminish with rise in hearing threshold suggests that it may be passive in origin. There are other data supporting the idea of a passive nonlinearity with a pattern of reversing polarity in cochlear mechanics (LePage *et al.*, 1980; LePage, 1981, 1987c).

Note added in proof: Much of the inherent difficulty throughout these capacitive probe studies has been due to suspecting that the nonlinear behavior of the basilar membrane was a sign of a second mode of motion, before motile behavior had been conclusively demonstrated in outer hair cells, and before the possibility of a major artifact was ruled out. The difficulty was compounded by the lack of adequate terminology to describe the second mode of the motion. It is at very least highly simplistic to portray the two components of the motion as being "ac" and "dc," but these terms have the advantage of being terse and do provide an initial conceptual grasp of the data.

The problem with ac and dc are these terms describe electric current flow, yet they are being borrowed for describing mechanical displacement. Also, dc strictly means a zero frequency component. It is clear that the long-term component does not have a steady value, so that it really constitutes a rate of change of position, or a velocity. Therefore, the term "dc displacement" is inappropriate on three counts, while the term "quasistatic" to describe the second mode is at best vague. It is not yet clear to what extent the long-term variation is repetitive, so the term "low-frequency" is no more elucidative. Moreover, the terms "zero-frequency" or "low-frequency" derive from linear systems theory and became inapplicable once the compressive nonlinearity was established. The term "drift" is likewise misleading because it carries the strong connotation of being monotonic and artifactual, which the component clearly is not.

Hence, the long-term component is described as a "summating baseline shift." While it appears to be an analog of the

summating potential, it is presumptive to conclude that it is, until the similarity of temporal characteristics of both electrical and mechanical phenomena is fully established. As suggested in the first of these papers (LePage, 1987a), the resolution of these difficulties can probably be obtained only after recognizing that, as with all nonlinear systems, no general method of analysis applies. Each nonlinear system requires individual consideration. In the case of the motion of the mammalian basilar membrane, it seems necessary to assume a provisional origin for each mode in order to find terms which adequately describe it. The traveling wave was originally described in the cochleas of cadavers so it is a passive response. There now exists a strong precedent that the second mode of the motion is indeed a motile response due to the outer hair cells. At this stage therefore, it seems no less appropriate, and a good deal more accurate, to denote this phenomenon as a *motile response* rather than a "dc component."

This study therefore developed the concept that the active response may be distinguished from the passive response not just on the basis of its physiological vulnerability, but also on the basis of available temporal and amplitude characteristics of the motile response of the outer hair cells. Second, investigation required the application the capacitive probe with its unique set of advantages. Third, the experimental procedures established the exacting conditions for which active and nonlinear behavior has been previously shown. The resulting data appears to have demonstrated the basic form of the motile response *in vivo* as a function of frequency.

ACKNOWLEDGMENTS

[1]The signal-to-noise improvement for the dc component is less than that for the ac component because it is computed as a difference of values from different time intervals, whereas the ac value is computed only during the burst.

[2]High-pass filtering the information on the second channel provides the added security that the dc component in the mechanical records is not due to crosstalk between the channels. In fact, the two sets of data have distinguishing features in their response properties.

Allen, J. B., Hall, J. L., Hubbard, A. E., Neely, S. T., and Tubis, A. (1986). *Peripheral Auditory Mechanisms* (Springer, Berlin, Lecture Notes in Biomathematics), Vol. 64.

Ashmore, J. F. (1985). Personal communication to D. C. Mountain.

Békésy, G. von (1960). *Experiments in Hearing* (McGraw-Hill, New York).

Brown, M. C., Nuttall, A. L., and Masta, R. I. (1983). "Intracellular recordings from cochlear inner hair cells: Effects of stimulation of the crossed olivocochlear efferents," Science 222, 69–71.

Brownell, W. E., Bader, C. R., Bertrand, D., and de Ribaupierre, Y. (1985). "Evoked mechanical responses of isolated cochlear outer hair cells," Science 227, 194–196.

Cody, A. R., and Russell, I. J. (1985). "Outer hair cells in the cochlea and noise induced hearing loss," Nature 315, 662–665.

Cook, R. O., and Hamm, C. W. (1979). "Fiber optic lever displacement transducer," Appl. Opt. 18, 3230–3241.

Dallos, P., Schoeny, Z. G., and Cheatham, M. A. (1972). "Cochlear summating potentials. Descriptive aspects," Acta Otolaryngol. Suppl. 302, 1–46.

Davis, H. (1958). "A mechano-electrical theory of cochlear action," Ann. Otol. Rhinol. Laryngol. 67, 789–801.

Davis, H. (1983). "An active process in cochlear mechanics," Hear. Res. 9, 79–90.

Davis, H., Deatherage, B. H., Eldredge, D. H., and Smith, C. A. (1958). "Summating potentials of the cochlea," Am. J. Physiol. 195, 251–261.

deBoer, E. (1969). "Reverse correlation II. Initiation of nerve impulses in the inner ear," Proc. Kon. Nederl. Akad. Wet. 72, 129–151.

deBoer, E., and Viergever, M. A., Eds. (1983). Proc. IUTAM/ICA Symposium, *Mechanics of Hearing* (Delft U. P., Delft, The Netherlands).

Evans, E. F., and Wilson, J. P. (1973). "The frequency selectivity of the cochlea," in *Basic Mechanisms in Hearing*, edited by A. R. Møller (Academic, New York), pp. 519–551.

Flock, Å. (1971). "Sensory transduction in hair cells," in *Handbook of Sensory Physiology*, edited by W. D. Keidel and W. D. Neff (Springer, Berlin), pp. 396–441.

Flock, Å. (1980). "Contractile proteins in hair cells," Hear. Res. 2, 411–412.

Flock, Å., Bretcher, A., and Weber, K. (1982). "Immunohistochemical localization of several cytoskeletal proteins in inner ear sensory and supporting cells," Hear. Res. 7, 75–89.

Hubbard, A. E., and Mountain, D. C. (1983). "Alternating current delivered into the scala media alters sound pressure at the eardrum," Science 222, 510–512.

Hubbard, A. E., Mountain, D. C., and LePage, E. L. (1986). "Furosemide effects ear-canal emissions produced by the injection of ac currents into scala media," in *Peripheral Auditory Mechanisms*, edited by J. B. Allen, J. L. Hall, A. Hubbard, S. T. Neely, and A. Tubis (Springer, Berlin, Lecture Notes in Biomathematics), Vol. 64, pp. 361–368.

Hudspeth, A. J., and Corey, D. P. (1977). "Sensitivity, polarity, and conductance change in the response of vertebrate hair cells to controlled mechanical stimuli," Proc. Natl. Acad. Sci. 74, 2407–2411.

Jesteadt W., and Norton, S. J. (1985). "The role of suppression in psychophysical measures of frequency selectivity," J. Acoust. Soc. Am. 78, 365–374.

Johnstone, B. M., and Boyle, A. J. F. (1967). "Basilar membrane vibration examined with the Mössbauer technique," Science 158, 389–390.

Kemp, D. T. (1978). "Stimulated acoustic emissions from within the human auditory system," J. Acoust. Soc. Am. 64, 1386–1391.

Khanna, S. M. (1983) (personal communication).

Khanna, S. M., and Leonard, D. G. B. (1982). "Basilar membrane tuning in the cat cochlea," Science 215, 305–306.

Khanna, S. M., and Leonard, D. G. B. (1986a). "Measurement of basilar membrane vibrations and evaluation of the cochlear condition," Hear. Res. 23, 37–53.

Khanna, S. M., and Leonard, D. G. B. (1986b). "Relationship between basilar membrane tuning and hair cell condition," Hear. Res. 23, 55–70.

Kim, D. O. (1986). "An overview of nonlinear and active cochlear models," in *Peripheral Auditory Mechanisms*, edited by J. B. Allen, J. L. Hall, A. Hubbard, S. T. Neely, and A. Tubis (Springer, Berlin, Lecture Notes in Biomathematics), Vol. 64, pp. 239–249.

Legouix, J. -P., Remond, M. -C., and Greenbaum, H. B. (1973). "Interference and two-tone inhibition," J. Acoust. Soc. Am. 53, 409–419.

LePage, E. L. (1981). The role of nonlinear mechanical processes in mammalian hearing, Ph.D. thesis (Univ. of Western Australia, Nedlands, Australia).

153   J. Acoust. Soc. Am., Vol. 82, No. 1, July 1987

Eric L. LePage: Basilar membrane "dc" components   153

LePage, E. L. (1987a). "The application of a capacitive probe technique for direct observation of electromechanical processes in the guinea pig cochlea," J. Acoust. Soc. Am. 82, 126–138.

LePage, E. L. (1987b). "Mammalian hearing: Does Helmholtz's harp tune to Corti's organ?" (submitted).

LePage, E. L. (1987c). "A passive, two-dimensional rectifier in the mammalian cochlea: Direct mechanical evidence and a model" (in preparation).

LePage, E. L., and Johnstone, B. M. (1980). "Nonlinear mechanical behaviour of the basilar membrane in the basal turn of the guinea pig cochlea," Hear. Res. 2, 183–189.

LePage, E. L., and Johnstone, B. M. (1981a). "Characterization of basilar membrane nonlinearity using the 'slope function,' " J. Acoust. Soc. Am. Suppl. 1 70, S8, D8.

LePage, E. L., and Johnstone, B. M. (1981b). "Short-term vulnerability and variability of basilar membrane nonlinearity," J. Acoust. Soc. Am. Suppl. 1 70, S8.

LePage, E. L., Johnstone, B. M., and Robertson, D. (1980). "Basilar membrane mechanics in the guinea pig cochlea—comparison of normals with kanamycin-treated animals," J. Acoust. Soc. Am. Suppl. 1 67, S45.

McCartney, J. C., Comis, S. D., and Pickles, J. O. (1980). "Is myosin in the cochlea a basis for active motility?," Nature 288, 491–492.

McMullen, T. A., and Mountain, D. C. (1985). "Model of d.c. potentials in the cochlea: Effects of voltage-dependent cilia stiffness," Hear. Res. 17, 127–141.

Mountain, D. C. (1980). "Changes in endolymphatic potential and crossed olivocochlear bundle stimulation alter cochlear mechanics," Science 210, 71–72.

Mountain, D. C. (1986). "Active filtering by hair cells, in Peripheral Auditory Mechanisms, edited by J. B. Allen, J. L. Hall, A. Hubbard, S. T. Neely, and A. Tubis (Springer, Berlin, Lecture Notes in Biomathematics), Vol. 64, pp. 179–188.

Mountain, D. C., Hubbard, A. E., and McMullen, T. A. (1983). "Electromechanical processes in the cochlea," in Symposium: Mechanics of Hearing, edited by E. deBoer and M. A. Viergever (Delft U. P., Delft, The Netherlands), pp. 119–126.

Neely S. T., and Kim, D. O. (1983). "An active cochlear model showing sharp tuning and high sensitivity," Hear. Res. 9, 123–130.

Patuzzi, R., Johnstone, B. M., and Sellick, P. M. (1984a). "The alteration of the vibration of the basilar membrane produced by loud sound," Hear. Res. 13, 99–100.

Patuzzi, R., Sellick, P. M., and Johnstone, B. M. (1984b). "The modulation of the sensitivity of the mammalian cochlea by low frequency tones. I. Primary afferent activity," Hear. Res. 13, 1–8.

Patuzzi, R., Sellick, P. M., and Johnstone, B. M. (1984c). "The modulation of the sensitivity of the mammalian cochlea by low frequency tones. III. Basilar membrane motion," Hear. Res. 13, 19–27.

Rhode, W. S. (1971). "Observations of the vibration of the basilar membrane in squirrel monkeys using the Mössbauer technique," J. Acoust. Soc. Am. 49, 1218–1231.

Rhode, W.S. (1973). "An investigation of post-mortem cochlear mechanics using the Mossbauer effect," in Basic Mechanisms in Hearing, edited by A. R. Møller (Academic, New York), pp. 49–63.

Rhode, W. S. (1978). "Some observations on cochlear mechanics," J. Acoust. Soc. Am. 64, 158–176.

Robertson, D. (1974). "Cochlear neurons: Frequency selectivity altered by perilymph removal," Science 186, 153–155.

Robertson, D., and Johnstone, B. M. (1979). "Aberrant tonotopic organization in the inner ear damaged by kanamycin," J. Acoust. Soc. Am. 66, 466–469.

Robles, L., Rhode, W. S., and Geisler, C. D. (1976). "Transient response of the basilar membrane measured in squirrel monkeys using the Mössbauer effect," J. Acoust. Soc. Am. 59, 926–939.

Russell, I. J. (1985) (personal communication).

Russell, I. J., and Ashmore, J. F. (1983). "Inner hair cell receptor potentials investigated during transient asphyxia: A model for hair cell coupling," in Proceedings of the 6th International Symposium on Hearing, Bad Nauheim, Germany, edited by R. Klinke and R. Hartmann (Springer, Berlin), pp. 10–15.

Russell, I. J., Cody, A. R., and Richardson, G. P. (1986). "The responses of inner and outer hair cells in the basal turn of the guinea-pig cochlea and in the mouse cochlea grown in vitro," Hear. Res. 22, 199–216.

Russell, I. J., and Sellick, P. M. (1978). "Intracellular studies of hair cells in the mammalian cochlea," J. Physiol. 284, 261–290.

Sachs, M. B., and Abbas, P. J. (1974). "Rate versus level functions for auditory-nerve fibers in cats: Tone-burst stimuli," J. Acoust. Soc. Am. 56, 1835–1847.

Sachs, M. B., and Kiang, N. Y. -S. (1968). "Two-tone inhibition in auditory-nerve fibers," J. Acoust. Soc. Am. 43, 1120–1128.

Schmiedt, R. A. (1982). "Effects of low-frequency biasing on auditory-nerve activity," J. Acoust. Soc. Am. 72, 142–150.

Sellick, P. M., and Russell, I. J. (1979). "Two-tone suppression in cochlear hair cells," Hear. Res. 1, 227–236.

Sellick, P. M., Patuzzi, R., and Johnstone, B. M. (1982). "Measurement of basilar membrane motion in the guinea pig using the Mössbauer technique," J. Acoust. Soc. Am. 72, 131–141.

Siegel, J. H., and Kim, D. O. (1982). "Efferent neural control of cochlear mechanics? Olivocochlear bundle stimulation affects cochlear biomechanical nonlinearity," Hear. Res. 6, 171–182.

Steele, C. R., and Zais, J. G. (1985). "Effect of opening and draining the cochlea," J. Acoust. Soc. Am. 78, 84–89.

Weiss, T. F. (1982). "Bidirectional transduction in vertebrate hair cells: A mechanism for coupling mechanical and electrical processes," Hear. Res. 7, 353–360.

Wiederhold, M. L. (1976). "Mechanosensory transduction in 'sensory' and 'motile' cilia," Ann. Rev. Biophys. Bioeng. 5, 39–62.

Wilson, J. P., and Johnstone, J. R. (1975). "Basilar membrane and middle-ear vibration in guinea pig measured by capacitive probe," J. Acoust. Soc. Am. 57, 705–723.

Zurek, P. M., and Clark, W. W. (1981). "Narrow-band acoustic signals emitted by chinchilla ears after noise exposure," J. Acoust. Soc. Am. 70, 446–450.