Effects of low-frequency biasing on spontaneous otoacoustic emissions: Frequency modulation

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It was previously reported that low-frequency biasing of cochlear structures can suppress and modulate the amplitudes of spontaneous otoacoustic emissions (SOAEs) in humans [Bian, L. and Watts, K. L. (2008). "Effects of low-frequency biasing on spontaneous otoacoustic emissions: Amplitude modulation," *J. Acoust. Soc. Am.* **123**, 887–898]. In addition to amplitude modulation, the bias tone produced an upward shift of the SOAE frequency and a frequency modulation. These frequency effects usually occurred prior to significant modifications of SOAE amplitudes and were dependent on the relative strength of the bias tone and a particular SOAE. The overall SOAE frequency shifts were usually less than 2%. A quasistatic modulation pattern showed that biasing in either positive or negative pressure direction increased SOAE frequency. The instantaneous SOAE frequency revealed a "W-shaped" modulation pattern within one biasing cycle. The SOAE frequency was maximal at the biasing extremes and minimized at the zero crossings of the bias tone. The temporal modulation of SOAE frequency occurred with a short delay. These static and dynamic effects indicate that modifications of the mechanical properties of the cochlear transducer could underlie the frequency shift and modulation. These biasing effects are consistent with the suppression and modulation of SOAE amplitude due to shifting of the cochlear transducer operating point. © 2008 Acoustical Society of America. [DOI: 10.1121/1.2990716]

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I. INTRODUCTION

Our inner ears are not only sound receivers but also sound generators. Even without an external acoustic stimulus, the inner ear can produce sounds that are called spontaneous otoacoustic emissions (SOAEs). These internally generated sounds are commonly identified by spectral analysis as tonelike peaks with frequencies distributed in the range from 0.5 to 5 kHz (see Probst *et al.*, 1991 for a review). On average, the number of the SOAE components is about 6 in each ear, but can be as many as 32/ear depending on the criterion for the detection of spectral peaks (Talmadge *et al.*, 1993). The amplitudes of these sounds are usually below 10 dB sound pressure level (SPL), thus rarely audible. If detection techniques are sensitive enough, SOAEs can be identified in up to 90% of normal hearing individuals (Pasanen and McFadden, 2000). The number of SOAE components, the distribution of SOAE frequencies, and their relative amplitudes are unique and relatively stable just like a "fingerprint" of a given inner ear.

Despite the relative stability and individual uniqueness, there are some remarkable differences in the features of SOAEs between genders and laterality. Females generally show more SOAE components with larger amplitudes than males (Bilger *et al.*, 1990). This gender difference may be a genetic trait or a consequence of differential influence of sexual hormones on embryonic neural development (McFadden, 2002). The prevalence of SOAE in the right ear is usu-

ally higher than the left (Kuroda, 2007). Such an asymmetry seems to indicate a correlation with the differential specialization of the central auditory system (Khalfa and Collet, 1996) or at least an influence of the efferent system (Mott *et al.*, 1989). These top-down connections between the brain and SOAEs in the inner ear suggest a possible involvement of outer hair cells (OHCs) in the formation of SOAEs because only these cells are largely innervated by efferent neural fibers from the brainstem. It is known that the OHCs are mechanically active due to their voltage-dependent motile responses in the cellular membrane (see Ashmore, 2008 for a review) or in the hair bundles (Martin *et al.*, 2003). The disinhibition due to irregular and sparse efferent innervations in the apical regions of the cochlea (Pujol, 2001; Thiers *et al.*, 2002) could allow such mechanical vibrations from the OHCs at certain locations to build up and eventually escape the boundary of the inner ear. The SOAEs may be carried out of the cochlea and stabilized by standing waves formed between the stapes footplate and these OHCs or other vibrating structures (Shera, 2003). The apical wave reflectors are scattered largely near the best frequency location of the SOAE. Hence, the OHC is a crucial element in the generation of SOAEs.

The essential function of the hair cells is to transform mechanical energy in sound into neural pulses through a transduction process which is known to be nonlinear. The transduction in OHC is bidirectional where mechanical vibrations from the reverse process could boost hearing sensitivity. The nonlinearity is responsible for a variety of auditory phenomena, such as compressive growth of cochlear responses, two-tone suppression, and generation of distortion

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product (Robles and Ruggero, 2001). These nonlinear features of OHC transducers are reflected in the behaviors of SOAEs to a range of experimental manipulations of cochlear mechanics. Presenting an external tone can suppress SOAEs and generate distortion products (Rabinowitz and Widin, 1984; Long *et al.*, 1993; Norris and Glatke, 1996). A suppression tuning curve can be constructed since the suppressor level has to be progressively reduced when its frequency approaches the SOAE (Bargones and Burns, 1988). It has been noticed that distortion product otoacoustic emissions (DPOAEs) elicited by two tones are larger in ears that generate SOAEs than those that do not (Ozturan and Oysu, 1999; Moulin, 2000). This observation indicates that the two different types of emissions could share a common element in their generating mechanisms which could be the nonlinear hair cell transduction.

Given that the cochlear nonlinearity is essential for normal hearing sensitivity and frequency selectivity, estimating the characteristics of the cochlear transducer has significant clinical utility in differential diagnosis of inner ear disorders. Toward this goal, a low-frequency biasing technique has been used to assess the dynamical nonlinearity of the inner ear (Bian *et al.*, 2002, 2004; Bian and Scherrer, 2007). The bias tone can shift the cochlear partition and produce an amplitude modulation (AM) of cochlear distortion products. The result shows that the amplitude change of the DPOAEs by the bias tone is consistent with the effect of a sigmoid-shaped transducer function. Since the cochlear transducer nonlinearity is sensitive to physiological and pathological alternations in the inner ear, it is hypothesized that mechanically varying the cochlear transducer gain could influence SOAEs. To test the hypothesis, the low-frequency biasing technique was applied to human subjects with large SOAEs (Bian and Watts, 2008). The results showed that SOAE amplitudes were suppressed and temporally modulated by the bias tone. The pattern of the SOAE magnitude variation resembled the first derivative of the sigmoid-shaped cochlear transducer function. In addition, it was noticed that the SOAE frequencies were changed by the bias tone. The frequency of SOAE is another sensitive indicator of alterations in cochlear mechanics since it can be influenced by body temperature (O'Brien, 1994), intracochlear pressure (de Kleine *et al.*, 2000), external sound (Long *et al.*, 1991, 1993), and activation of the efferent system (Mott *et al.*, 1989). This paper investigates the frequency shift and frequency modulation (FM) of SOAEs under low-frequency biasing.

II. METHODS

A. Experimental procedures

The experimental procedures were described in the earlier report (Bian and Watts, 2008). Briefly, 11 normal hearing ears were selected for having at least one large SOAE which was defined by a greater than 20 dB signal-to-noise ratio (SNR). The ear-canal acoustics were recorded with a calibrated probe microphone (Etymotic Research, ER-10B+) while presenting a low-frequency bias tone with an insertion earphone (HA-FX55, JVC). The bias tone was digitally gen-

erated and controlled with software implemented in LABVIEW [Version 8, National Instruments (NI)]. The bias tone was delivered from a 24 bit dynamic signal acquisition and generation card (PXI-4461, NI) at 25, 32, 50, 75, and 100 Hz. To result in a 1 Hz frequency resolution in subsequent spectral analyses, the duration of the bias tone was set to 1 s. At each bias tone frequency (f_{bias}), the peak amplitude was attenuated automatically from 3 or 4 Pa to 0 in 41 steps. The maximal biasing pressure used was determined by increasing the bias tone level (L_{bias}) until a significant amplitude reduction in the largest SOAE was observed. At each biasing step, the recorded ear-canal signal was amplified 20 dB, averaged up to 16 times, and digitized at a sampling frequency (f_{samp}) of 204.8 kHz. This procedure was repeated with a 20 min break to measure the variability and repeatability of the biasing effects between the two trials.

B. Signal processing and data analysis

1. General spectral analysis

Data were analyzed off-line in MATLAB (Version 7, MathWorks). A general spectral analysis was applied to the signals collected at different L_{bias} to extract the features of the SOAEs. First, the entire signal was high pass filtered at 400 Hz to eliminate the bias tone and submitted to a fast Fourier transform (FFT) to obtain a set of 41 spectra. Second, the SOAE components were identified as spectral peaks with 20 dB SNR in the absence of a bias tone, and their baseline frequencies and amplitudes were recorded. Third, SOAE frequencies were extracted across all records. For conditions when a SOAE was suppressed, the SOAE frequency (f_{SOAE}) was determined by the largest spectral peak within $\pm 3f_{\text{bias}}$ from the baseline value. Finally, the amplitudes of sidebands above and below the SOAE component or the upper and lower sidebands (USBs and LSBs) were measured. Spectral sidebands, typical for both AM and FM signals, were located with frequency intervals of integer multiples of the f_{bias} from the SOAE. Two LSBs and USBs, namely, sidebands I and II that are f_{bias} and $2f_{\text{bias}}$ away from the SOAE [Fig. 1(A)], were used in further analyses.

2. Quasistatic modulation pattern

To examine the influence of biasing directions on f_{SOAE} , a quasistatic modulation pattern (Bian *et al.*, 2002; Bian and Chertoff, 2006) was obtained with analyzing windows fixed at the peaks and troughs of the bias tones [Fig. 1(B)]. The window length (l_{win}) was limited within one-half biasing cycle to ensure that the biasing effect on SOAEs was due to a "static" displacement of the cochlear partition in the same direction. Detecting small frequency changes in SOAE required high-resolution spectral analyses, thus a short-time FFT was insufficient. Alternatively, these short-analyzing windows were linked [Fig. 1(B)] to yield a long time sequence, thus a significant reduction in frequency resolution could be avoided. Due to the periodicity of the repeating windows, a consequence of this linked-window method was the production of harmonic peaks that could interfere with the measurement of SOAE components. This could be largely eliminated by adjusting the l_{win} in a few trials. Ini-

FIG. 1. Analysis methods. (A) A spectrum of the ear-canal signal and the spectral window method. The box represents a rectangular window centered at a SOAE containing two sidebands on each side. The windowed contents are submitted to an IFFT to extract the temporal features of the SOAE. LSBs: lower sidebands; USBs: upper sidebands. Sidebands I: frequency spacing with the SOAE equals f_{bias} ; sidebands II: frequency spacing with the SOAE equals $2f_{\text{bias}}$. (B) Linked-window method. Temporal windows located at the peaks and troughs of a sequence of bias tones with various amplitudes are linked, respectively, for spectral analysis. The calculated SOAE amplitudes and frequencies represent the two halves of the quasistatic modulation pattern in the positive and negative sound pressure directions, respectively.

tially, six different l_{win} were selected from a set of values ranging between $\frac{1}{4}$ and $\frac{1}{2}$ biasing cycle with a $\frac{1}{16}$ cycle increment, i.e., $l_{\text{win}} = (n/16)N_{\text{bias}}$, where N_{bias} is the number of points within a biasing cycle given by $f_{\text{samp}}/f_{\text{bias}}$ and $n = 3, 4, \dots, 8$. For each l_{win} , the frequency difference between the f_{SOAE} and the closest harmonic of f_{bias} was calculated. The l_{win} with the largest frequency difference was selected, and the analyzing windows were linked for FFT. If the frequency of SOAE obtained with the linked-window method (f'_{SOAE}) from the no-biasing condition drifted from the baseline f_{SOAE} , then the frequency ratio ($f'_{\text{SOAE}}/f_{\text{SOAE}}$) was used as a factor to further adjust the window length:

$$l_{\text{win}} = \frac{n}{16} \frac{f'_{\text{SOAE}}}{f_{\text{SOAE}}} N_{\text{bias}}. \quad (1)$$

This adjustment could ensure accuracy in f_{SOAE} estimation and eliminate the harmonics generated by linked windows. Then, the new time sequences were zero padded on both ends to result in a 1 Hz frequency resolution in FFT. Finally, the SOAE frequencies obtained for the negative and positive biasing pressures were combined to form a quasistatic modulation pattern.

3. Period modulation pattern

A spectral windowing method was employed to extract the temporal pattern of the SOAE frequency variation [Fig. 1(A)]. The positive half of the complex spectrum of the ear-canal signal was selected by a rectangular window centered at the f_{SOAE} . Initial analysis indicated that the SOAE frequency change (Δf_{SOAE}) was small compared to the f_{bias} , and only the two sidebands closest to the SOAE in both LSB and USB contained most energy. Therefore, a narrower bandwidth of the spectral window than the AM analysis (Bian, 2006; Bian and Watts, 2008) was determined (see Appendix and Fig. 12 for details):

$$B_{\text{FM}} = 2(\Delta f_{\text{SOAE}} + 2f_{\text{bias}}). \quad (2)$$

The windowed complex spectrum was submitted to an inverse fast Fourier transform (IFFT) to obtain an analytic signal of the frequency modulated SOAE. Its instantaneous frequency (f_i) was calculated by the derivative of the unwrapped phase (φ) with respect to time:

$$f_i(t) = \frac{f_{\text{samp}}}{2} \frac{1}{2\pi} \frac{d\varphi}{dt}, \quad (3)$$

where $f_i(t)$ is a time waveform representing the f_{SOAE} . A two-point average smoothing was applied to the phase derivative to reduce the roughness or variability, and the waveform was down sampled to $\frac{1}{20}$ of the f_{samp} for further use. To establish the correlation between the temporal features of f_{SOAE} with the bias tone phase, the f_{SOAE} waveform was truncated based on each of the 22–88 biasing cycles and averaged to reduce noise. This resulted in a period modulation pattern of the f_{SOAE} for each biasing step.

III. RESULTS

A. Spectral fine structures

1. Upward frequency shift

Since the general characteristics of SOAEs and the biasing effects on SOAE amplitudes in these ears were described in a preceding report (Bian and Watts, 2008), the present paper focuses on the frequency change induced by the bias tone. The frequencies and magnitudes of SOAEs were highly dependent on each individual ear; thus the results will be reported using examples and efforts will be made to reflect the general trends in all observations. To examine the frequency change, the variability due to random error in frequency analysis and normal frequency fluctuation over time were assessed by checking repeated measures of the baseline f_{SOAE} at the last biasing step ($L_{\text{bias}}=0$). Averaged

FIG. 2. Upward frequency shift of SOAE with L_{bias} . A sequence of spectra focused on a SOAE with an increase in the L_{bias} demonstrates an upward-frequency shift of the SOAE. Each spectrum has been shifted 40 dB with respect to the next to avoid overlap. Note that some spectra without obvious frequency shift at lower L_{bias} are omitted.

across all ears and bias tone frequencies, the standard deviations for trials 1 and 2 were about 2 and 1.5 Hz, respectively. The change in the baseline f_{SOAE} between the two trials averaged across all emission components in all ears was about +1 Hz. However, this increase in baseline f_{SOAE} was within the 2 Hz standard deviation of the baseline f_{SOAE} estimated across trials. Unless otherwise noted, the SOAE frequencies of the two trials were averaged. This analysis indicated that any SOAE frequency shift, if more than 2 Hz, could be considered as significant change.

The most important findings of the study were an upward shift of the f_{SOAE} and a suppression of the SOAE magnitude due to the presence of the bias tone. Even though the amount of frequency shift was commonly less than 20–40 Hz, the frequency shift was certainly noticeable when comparing spectra obtained at low versus high bias tone levels (Fig. 2). The direction of the frequency shift was always an increase which occurred in most of the SOAEs from all ears. These upward-frequency shifts could readily be observed under moderate to high bias tone levels, usually between around 70 and 100 dB SPL where there was no significant SOAE amplitude reduction. When the SOAE amplitude started to be suppressed, the frequency shift became more dramatic, sometimes accompanied by a widening of the spectral peak. At lower bias tone levels (<65–85 dB SPL), only a fluctuation of the f_{SOAE} could be observed while the SOAE amplitude remained unaffected.

FIG. 3. Spectral effects of L_{bias} on a SOAE: frequency shift, generation of sidebands, and suppression. Spectra shown are obtained at moderate to high bias tone levels where these effects are usually observed. The sidebands ($\blacktriangle$) are presented at integer multiples of the f_{bias} from the SOAE, thus shifting with the SOAE. Note that the sidebands initially increase with the L_{bias} and then fall as the SOAE is suppressed. Sidebands I and II: frequency spacing with f_{SOAE} equals f_{bias} and $2f_{\text{bias}}$, respectively.

2. Spectral sidebands

Another frequency-domain observation was the presence of multiple sidebands around the SOAE when relatively high bias tone levels were used. In most cases, the sidebands were detected between 80 and 90 dB SPL L_{bias} where SOAE amplitudes were stable (Fig. 3). The number and sizes of the sidebands on either side of the SOAE varied depending on the bias tone strength relative to the SOAE (middle panels). Under strong influence of the bias tone, there were usually large multiple sidebands that could mostly be attributed to the AM of the SOAE (Bian and Watts, 2008). At very high biasing levels where the SOAEs were suppressed, the sizes of the sidebands also decreased (top panel). As the L_{bias} became weaker (<90–100 dB SPL), one or two smaller sidebands appeared on each side of the SOAE. These sidebands could mainly come from the FM of the SOAE because the SOAE amplitude was stable at the maximal value. Usually, sidebands I in either LSB or USB were the largest in magnitude. Then the next prominent sidebands were sidebands II. More distant sidebands were generally very small or absent. When the L_{bias} was below 70 dB SPL, typically no sidebands were observed (bottom).

As the L_{bias} increased, the frequency and amplitude of SOAE demonstrated some opposite behaviors (Fig. 4). The

FIG. 4. Biasing effects on SOAE frequency, amplitude, and sidebands. (A) An upward-frequency shift of SOAE with the L_{bias} . (B) Suppression of the SOAE amplitude (top trace) and growth of sidebands (lower trace). The f_{SOAE} starts to increase before its amplitude is significantly reduced. The sideband becomes measurable at a much lower L_{bias} (75 dB SPL). Data are average of the two trials.

changes of sidebands were represented by the relatively large sidebands I in the LSB and USB (lower trace in panel B). When L_{bias} was below 85 dB SPL, the SOAE magnitude fluctuated around 5 dB SPL without any frequency change. When the L_{bias} exceeded 85 dB SPL, the f_{SOAE} started to rise, the sideband grew continuously, and the SOAE magnitude began to fall. Above 95 dB SPL, the SOAE was significantly suppressed and sideband showed a rollover (panel B), while the f_{SOAE} reached a maximal value (panel A). The growth of the sidebands became noticeable when the L_{bias} was over 75 dB SPL and was steeper above 88 dB SPL. From this L_{bias} to where the sidebands reached their peaks, both the SOAE frequency and amplitude were unstable and eventually proceeded to opposite changes.

3. Frequency effects

It was observed that the biasing effects on a SOAE were highly dependent on the relative frequency difference between the bias tone and the SOAE. The bias tone was more effective when the f_{bias} was closer to the f_{SOAE} . The influence of bias tones with different frequencies on the same SOAE reflected a range of such effectiveness [Fig. 5(A)]. The 100 Hz bias tone was the most effective since at only 65 dB SPL it could cause a frequency increase and a 13 Hz shift at 84 dB SPL. The 32 Hz bias tone was the weakest one because the f_{SOAE} remained relatively unchanged until the L_{bias} reached above 85 dB SPL and the frequency shift was smaller. SOAE frequency shifts for bias tones of 75 and 50 Hz were distributed in between. The effectiveness of a bias tone could also be evident by frequency shifts of multiple SOAEs [Fig. 5(B)]. It could be observed that the bias tone was much more effective in producing a frequency shift of a 942 Hz SOAE than other SOAEs with higher frequencies. For SOAEs of 1800 Hz or higher, the L_{bias} had to be greater than 100 dB SPL to produce any measurable frequency shift. This range of effects indicated that the bias tone was less effective when the SOAE frequency locations were farther away from the cochlear apex.

FIG. 5. Frequency shifts: differential effects of f_{bias} and f_{SOAE} . (A) A sequence of traces showing the frequency shift of a SOAE at 1691 Hz under the influence of bias tones with different frequencies. Note that the f_{SOAE} begins to increase at a lower L_{bias} and can reach a higher final maximal value as the f_{bias} increases. (B) Frequency shifts from the baseline values for a set of SOAEs under the influence of a 32 Hz bias tone. The bias tone is more effective for lower-frequency SOAEs since lower bias tone levels are required. Data are average of the two trials.

Data compiled from all the SOAEs under various biasing conditions showed such a reduction in biasing effect with f_{SOAE} (Fig. 6). Two quantities could be assessed from the data: the maximal Δf_{SOAE} and the L_{bias} required to produce a just noticeable frequency shift of 2 Hz. For a fixed f_{bias} , the maximal Δf_{SOAE} decreased as the f_{SOAE} increased (Fig. 6, top row). These results suggested that the influence of the bias tone diminished while the SOAE frequency place moved toward the cochlear base. Depending on the f_{bias} , the rate of reduction in biasing effects varied from roughly -6 to -16 Hz/octave increase in f_{SOAE} . For an ear with multiple SOAEs spreading from 1 to 5 kHz, the frequency shift was mostly observed below 3–4 kHz. Moreover, the Δf_{SOAE} increased mainly from about 10 to 30 Hz when the f_{bias} varied from 25 to 100 Hz. These frequency shifts amounted to approximately 1%–2% of the baseline f_{SOAE} . The second quantity, the L_{bias} needed to observe a minimal Δf_{SOAE} , increased with the f_{SOAE} (Fig. 6, bottom row). This indicated that one had to increase the L_{bias} or reduce the frequency difference between the bias tone and the SOAE to observe an effect. The rate of level increase seemed to be constant across all the bias tone frequencies. A rough estimate showed that the demanding of the biasing power increased at a rate of 8 dB/octave rise in f_{SOAE} . The L_{bias} for minimal Δf_{SOAE} ranged from 65 to 95 dB SPL for f_{bias} of 100 and 25 Hz, respectively.

B. Quasistatic modulation pattern

Quasistatic modulation patterns obtained from linked segments of the acoustic signal fixed at peaks and troughs of bias tones of various amplitudes provided a measure of f_{SOAE} variations as a result of biasing cochlear structures in opposite directions. A pair of exemplary f_{SOAE} modulation patterns from an ear showed similar characteristics across the

FIG. 6. Maximal SOAE frequency shift and effective bias tone levels. Top row: The maximal frequency shifts of all SOAEs under the influence of bias tones at different frequencies. The approximated reduction rate in the maximal frequency shift ranging from -6 to -16 Hz/octave is depicted by a thicker line in each panel. Bottom row: The bias tone levels required to produce a minimal frequency shift of 2 Hz for all the SOAEs are shown for different bias tone frequencies. Generally, it requires more sound pressure to produce a frequency shift for higher-frequency SOAEs. The rate of reduction in the bias tone efficiency is roughly 8 dB/octave (thicker lines) regardless of the f_{bias} . Data are average of the two trials.

two trials (Fig. 7). The f_{SOAE} was minimal around zero biasing pressure and shifted upward when the biasing pressure stepped up in either direction. The “U-shaped” modulation pattern expanded between ± 3 Pa biasing pressures and revealed a modulation depth, the difference between the maximal and minimal SOAE frequencies, of about 15–20 Hz. The f_{SOAE} showed large fluctuations at the extremes of the biasing pressures. This increased variability was a consequence of suppressions of SOAE to the noise floor, leading to random errors in the frequency estimation. A smaller fluctuation of the f_{SOAE} in the amount of 3–4 Hz due to low biasing pressures could also be noted at the bottom of the modulation patterns.

FIG. 7. Quasistatic modulation patterns of f_{SOAE} . Biasing in either positive or negative sound pressure directions increases the f_{SOAE} . Fluctuation of the f_{SOAE} about the baseline value (3148 Hz) can be observed around zero biasing pressure. Data obtained from the two trials with the linked-window method are consistent.

There were frequency-dependent variations in the quasistatic modulation patterns. This could be observed by examining the behavior of a single SOAE under different biasing frequencies (Fig. 8, left column). As the f_{bias} increased (from bottom up), the modulation depth increased and the width reduced. The modulation depth varied from about 20 to 45 Hz as the f_{bias} was elevated from 25 to 100 Hz. The modulation width, the range of biasing pressures between the maximal SOAE frequencies, expanded across ± 1 Pa at 25 Hz biasing condition and gradually narrowed to only ± 0.5 Pa when the f_{bias} was above 75 Hz. Larger frequency shifts at lower biasing pressures indicated that higher-frequency bias tones were more effective. The second frequency effect could be evident from a single ear as the modulation patterns of different SOAEs by the same bias tone (Fig. 8, right column). As the f_{SOAE} increased (from top down), the modulation patterns became wider and shallower, implying a weakening of the biasing effect. The SOAE magnitude and frequency also influenced the modulation pattern. Larger emissions (e.g., 1.95 kHz) showed a better defined pattern with less fluctuation. Lower-frequency SOAEs (e.g., 1.5 kHz) were easily suppressed by the bias tone, thus showing a shallower pattern. For larger SOAEs, more frequency shifts could be achieved but at higher biasing pressures.

C. Period modulation pattern

It should be noted that the SOAEs were nonstationary signals since their amplitudes and frequencies varied depending on the relative power of the external tone and the direction of mechanical biasing. It was necessary to analyze the temporal property of the f_{SOAE} in relation to the cyclic biasing of cochlear structures. The instantaneous f_{SOAE} wave-

FIG. 8. Quasistatic modulation patterns: frequency effects. Left column: Effect of f_{bias} on a SOAE at 1691 Hz. From top to bottom, as f_{bias} decreases, the width of the pattern increases, and the modulation depth decreases. Note that at both biasing extremes, especially, for $f_{\text{bias}} > 75$ Hz, the f_{SOAE} shows large variations due to significant suppressions of the SOAE. Right column: Effects of a 50 Hz bias tone on four SOAEs in an ear. From top to bottom, as f_{SOAE} increases, the modulation pattern becomes shallower and wider. The modulation pattern is also influenced by the SOAE amplitude, e.g., the best defined pattern is that of the largest SOAE (1955 Hz).

form obtained from IFFT demonstrated some periodicity and randomness [Fig. 9(A)]. When closely examined with respect to the corresponding bias tone, it could be found that there were three maxima and two minima in one biasing cycle. This regularity was verified by performing a FFT on the f_{SOAE} waveform [Fig. 9(B)]. A large spectral peak was revealed at the second harmonic of the bias tone or $2f_{\text{bias}}$, indicating that a pattern appeared in every half biasing cycle. Another way of examining the dynamic frequency change was to study the distribution of frequency points by constructing a histogram over the entire waveform [Fig. 9(C)]. The histogram showed two features of the f_{SOAE} : peak splitting and exact bandwidth. Peak splitting implied that the f_{SOAE} oscillated between two values, the baseline and a maximum, similar to a sinusoid wave. The width of the histogram as obtained by the 5th and 95th percentiles of the cumulative distribution of frequencies provided a measure of the variability of f_{SOAE} , i.e., 90% of the frequencies occurred within this range. Such a range could be supplied to Eq. (2) to refine the filter bandwidth for analyzing the FM signal.

Because the bias tones could modulate both SOAE amplitude and frequency (Figs. 2–4), for a given f_{bias} , instantane-

ous frequencies obtained from moderate bias tone levels (< 95 – 100 dB SPL) with no SOAE suppression were examined to determine the temporal modulation pattern. The instantaneous f_{SOAE} showed some large transient fluctuations [Fig. 9(A)] that could partially be related to random variations in SOAE amplitude. To further reduce the random errors in frequency estimation, a period modulation pattern was derived from averaging the instantaneous f_{SOAE} over a majority of the biasing cycles. Other periods where the instantaneous frequency exceeded the 90% confidence range were excluded from averaging. Only when more than half of the total biasing periods were included for averaging was a period modulation pattern considered valid [Fig. 9(D)]. The period modulation pattern typically showed a “W” shape: a center peak and two notches. Compared with the bias tone, frequency peaks occurred at the biasing extremes, and minima were close to zero crossings of the bias tone. Stronger SOAEs were more likely to show the typical pattern in more biasing cycles.

For a fixed f_{bias} , this typical modulation pattern varied with the L_{bias} . Two trends could be observed with the reduc-

FIG. 9. Characteristics of temporal pattern of f_{SOAE} . (A) The instantaneous frequency of a SOAE in relation to the bias tone (lower trace). Compared with the bias tone cycles, it can be observed that the f_{SOAE} peaks three times in a biasing period. (B) A spectrum of the f_{SOAE} waveform in panel A. The most prominent spectral peak appears at 64 Hz or $2f_{\text{bias}}$, indicating that a pattern occurs twice in a biasing cycle. (C) A histogram of the oscillating f_{SOAE} shows peak splitting. The left branch of the peak is related to the baseline f_{SOAE} . The frequency variation is mostly within a 40 Hz bandwidth between the 5th and 95th percentiles. Frequency bin=1 Hz. (D) A period modulation pattern obtained by averaging the f_{SOAE} waveform over multiple biasing cycles. The minima and maxima of the W-shaped pattern correspond to the zero crossings and extremes of the bias tone. Note that segments of the f_{SOAE} waveform with variability beyond the 90% interval are not included in the averaging. The ratio of included cycles vs the total number of biasing periods is indicated. τ is the averaged time delay of the f_{SOAE} modulation pattern.

tion in biasing pressure: a decrease in frequency excursion and prolonged delays of f_{SOAE} extremes (Fig. 10). As the L_{bias} was attenuated about 20 dB from 97 dB SPL, the range of f_{SOAE} oscillation subsided from about 25 to just 10 Hz. The frequency minima could be lower than the baseline value. The frequency increases at the biasing pressure extremes were not even. It was noticeable that the peaks and troughs of the f_{SOAE} were delayed with respect to the bias tone as the L_{bias} decreased. The averaged time delay (τ) of the f_{SOAE} maxima and minima was only 0.3 ms at 97 dB SPL L_{bias} and nearly 3.6 ms at the 77 dB SPL condition.

The period modulation pattern of a SOAE also varied with the f_{bias} (Fig. 11). As the f_{bias} increased from 25 to 100 Hz, the range of f_{SOAE} oscillation doubled from 30 to 60 Hz. Larger frequency oscillation was also marked by the minima below baseline value at zero crossings of the bias tone. Moreover, the typical FM patterns were observed at lower bias tone levels when the f_{bias} was higher. For example, the L_{bias} of 91 dB SPL at 25 Hz that induced a FM had to be attenuated by 10 dB when the f_{bias} was increased to 100 Hz. This was consistent with the two-tone interactions within the cochlea, i.e., suppression and distortion are more effective when the two frequencies are close. Thus, the bias tones with higher frequencies were more effective in producing f_{SOAE} oscillations. The effect of f_{bias} on delays of the f_{SOAE} pattern was variable. A slight reduction in the averaged time delay was shown as the f_{bias} increased. Moreover, the typical f_{SOAE} modulation patterns were more commonly found at lower biasing frequencies.

IV. DISCUSSION

A. Upward frequency shift of SOAE

The general effect of low-frequency biasing on f_{SOAE} is an upward shift. The analysis reveals that the frequency shift can reach up to about 2% of the baseline value depending on the bias tone power and the strength of a SOAE (Figs. 2–6). Consider the suppression of SOAE reported earlier (Bian and Watts, 2008), the biasing effects are opposite on SOAE magnitude and frequency, i.e., a reduction in SOAE amplitude is accompanied by an increase in frequency (Figs. 2–4). This is consistent with other observations using an external tone to suppress SOAEs (Long *et al.*, 1991, 1993; Norrrix and Glatke, 1996). These studies show that when the suppressor frequency is below a SOAE, it can “push” the f_{SOAE} away from its original value, i.e., an upward shift. Such opposite changes in SOAE level and frequency seem to correlate with the effect of varying the inner ear pressure. Increasing and decreasing the ear-canal air pressure can change the f_{SOAE} (Schloth and Zwicker, 1983; Hauser *et al.*, 1993) similar to the quasistatic modulation patterns (Figs. 7 and 8). The canal pressure change in the magnitude of several kilopascals designed to modify the middle ear properties would unavoidably influence the inner ear pressure and the f_{SOAE} . Another indirect way of varying the inner ear pressure can be achieved by a posture change because the intracranial pressure could be transmitted to the inner ear fluid via the cochlear aqueduct. The f_{SOAE} can be shifted up to 2% with a reduction in amplitude when the body is tilted from upright to supine position (de Kleine *et al.*, 2000). Most of these

FIG. 10. Period modulation patterns: effects of L_{bias} on f_{SOAE} . From top to bottom, as L_{bias} decreases, the frequency excursion becomes smaller and the temporal features of the FM pattern lag the bias tone (bottom trace). The time delay (τ) averaged across the f_{SOAE} maxima and minima is indicated in each panel. For each half biasing cycle, the f_{SOAE} shows a minimum below the baseline value (arrow) following a bias tone zero crossing. The ratio of included cycles over the total biasing periods is indicated. The baseline f_{SOAE} is 2503 Hz.

frequency shifts are less than 20 Hz which is comparable to the present study (<50 Hz) since the biasing effects could be greater than a posture change. These observations indicate that the SOAE amplitude is largest and the frequency is lowest when the inner ear pressure is optimally balanced.

Pressure change in the inner ear could alter certain mechanical properties of the structures that are initializing or reflecting SOAE standing waves. It is generally agreed that the cochlear partition could be considered as a series of single-degree-of-freedom oscillators (Dallos, 1996). The natural frequency (ω_n) of each element is determined by the stiffness (k) and mass (m) or $\sqrt{k/m}$. It is apparent that to increase ω_n , one could either raise k or decrease m . Applying a bias tone could generally stiffen the cochlear partition, thus increasing the f_{SOAE} . If a group of oscillators at a particular section on the cochlear partition contribute to form a SOAE, then more apical elements in the group could be suppressed by the bias tone. This would result in a shift of contribution to relatively basal oscillators with a smaller net cellular m and larger k . The 1%–2% SOAE frequency shift (Fig. 6) seems to indicate a bandwidth that the group of oscillators is

tuned to. If the bandwidth represents the boundary on the cochlear partition where OHCs are active components, then it is possible to estimate the population of the OHCs contributing to the SOAE. According to a cochlear frequency map (Greenwood, 1990), the characteristic frequency (f_{CF}) location as a distance (x) in millimeters from the apex can be calculated: $x = (1/a) \log_{10}(f_{\text{CF}}/A + k)$, where $a = 0.06 \text{ mm}^{-1}$, $A = 165 \text{ Hz}$, and $k = 1$ for humans. Consider a frequency shift of 2%, the distance between two locations with a frequency ratio of 1.02 can be obtained:

$$\Delta x = \frac{1}{a} \log_{10} \left(\frac{1.02 f_{\text{CF}} + A}{f_{\text{CF}} + A} \right). \quad (4)$$

This distance ranging from 0.1 mm at 500 Hz to about 0.14 mm for higher frequencies coincides with the extent of efferent innervations of a single fiber in the organ of Corti which rarely exceeds $150 \text{ } \mu\text{m}$ (Robertson and Gummer, 1985). If the diameter of an OHC is $8 \text{ } \mu\text{m}$, then this range of distance on the cochlear partition could hold about 12–18 OHCs in one row or a total of 36–54 cells for three rows. It seems to suggest that irregularities in efferent connections to the OHCs may give rise to SOAEs. It also indicates that the SOAE could be present in a relatively restricted region in the cochlea. This localized SOAE production could be evident by the limited efficiency of the bias tone in influencing SOAEs with higher frequencies (Figs. 5 and 6). The 8 dB/octave increment of power demand for the bias tone to produce an effect on SOAEs (Fig. 6; Bian and Watts, 2008) and DPOAEs (Hensel *et al.*, 2007; Marquardt *et al.*, 2007; Bian and Scherrer, 2007) is inline with the tails of the mechanical tuning curves of the basilar membrane. Indeed, spontaneous oscillation has been expectedly observed at a specific location on the basilar membrane in a guinea pig with a SOAE (Nuttall *et al.*, 2004).

B. Opposite changes of SOAE magnitude and frequency: A transduction mechanism

The opposite biasing effects of SOAE amplitudes and frequencies are consistent with other observations in humans: correlated fluctuation of SOAE amplitude and frequency over time (Whitehead, 1991), contralateral acoustical stimulation (Mott *et al.*, 1989), and ipsilateral noise exposure (Kemp, 2007). Similar opposite behaviors of SOAE are found in manipulations of inner ear Ca^{2+} concentration in skinks (Manley *et al.*, 2004), noise exposure in lizards (Manley, 2006), dc injection in frogs (Wit *et al.*, 1989), and hypoxia in guinea pigs (Ohyama *et al.*, 1991). These evidences imply that the SOAE magnitude and frequency undergo correlated and opposite changes (van Dijk *et al.*, 1994) when the inner ear function is modified. Despite the drastic differences in inner ear anatomies among different species, a similar structural and functional element is the hair cell transduction which converts sound vibrations to electrical signals. In fact, there is an electrical counterpart of SOAE that can be recorded with an electrode placed in the inner ear (Wit *et al.*, 1989; Ohyama *et al.*, 1991). Therefore, the hair cell transduction could contribute to the generation of SOAEs.

FIG. 11. Period modulation patterns: effects of f_{bias} on a SOAE. As f_{bias} increases, the frequency excursion becomes larger and the typical modulation patterns can be observed at lower biasing levels. Note that the f_{SOAE} minima can be lower than the baseline value (arrow). The time delay (τ) of the f_{SOAE} is slightly reduced with the f_{bias} . Numbers of included cycles are marked.

The suppression and modulation of SOAE amplitude can be interpreted by an operating point shift along the sigmoid-shaped cochlear transducer function which has a maximal gain at the inflection point (Bian and Watts, 2008). In the case of f_{SOAE} change, it could be attributed to the modulation of the stiffness in a section of the cochlear partition that is involved in the formation of a SOAE. The most variable constituent of the cochlear partition stiffness is probably contributed by the stereocilial bundles of OHCs because of their critical position between the tectorial membrane and reticular lamina where the mechanical deformation is maximal. Moreover, about 30%–40% of the hair bundle stiffness can be attributed to the gating springs (Kros, 1996), the molecular linkages that open and close the transduction channels. Therefore, the gating and adaptation motors in the hair bundles could be a factor responsible for the f_{SOAE} shift under low-frequency biasing.

The most important feature of the gating stiffness of hair bundles is the dip around their resting positions where 50% of transduction channels are open (Markin and Hudspeth, 1995). The relative hair bundle stiffness change (Δk) from unity can be determined by the probabilities of channel opening (P_0) and closing ($1 - P_0$), where P_0 is dominated by a saturating nonlinearity, such as a Boltzmann function. If hair cells contribute to half of the cochlear partition stiffness, for constant m , the change in resonant frequency ($\Delta\omega$) is proportional to the square root of Δk , i.e.,

$$\Delta\omega \text{ (%) } \propto \sqrt{1 - 0.5\delta P_0(1 - P_0)}, \quad (5)$$

where $\delta=0.3\text{--}0.4$ represents the portion of the bundle stiffness contributed by the nonlinear gating spring. This relation qualitatively predicts the U-shaped quasistatic modulation pattern of f_{SOAE} with a $\Delta\omega$ of 1%–2% which is consistent

with the experimental results. The shape of the gating stiffness depicts a second-order nonlinearity which was used in a van der Pol oscillator to model the fluctuations of SOAE amplitude and frequency (van Dijk and Wit, 1990). Increase in stiffness with displacement, a feature of the Duffing oscillator exhibiting a frequency shift (Talmadge *et al.*, 1991), can explain the FM of tone-evoked cochlear microphonic generated by the OHCs (Chertoff *et al.*, 2000). Therefore, both the amplitude and frequency of SOAEs could be related to the nonlinearity in the cochlear transducer.

C. Temporal effects

The dynamic aspect of the low-frequency biasing is represented by the temporal modulation of the f_{SOAE} . The FM typically occurs at relatively lower bias tone levels (75–95 dB SPL) when there is no significant AM, whereas typical AM is observed at higher levels (>95–100 dB SPL). This may indicate that the f_{SOAE} is more sensitive than the amplitude to mechanical alterations in the inner ear or less susceptible to noise contamination (Long and Talmadge, 1997). Tracking the SOAE amplitudes and frequencies over time with ipsi- or contralateral acoustic stimulations indicates that most of the f_{SOAE} reductions are statistically significant compared to nonsignificant SOAE amplitude increases (Whitehead, 1991). These changes are hypothesized to be a micro-mechanical effect of resetting the operating point of the hair cell transducer to its optimal position after an efferent activation (Bian, 2004). Such a high sensitivity of f_{SOAE} to minor alterations in cochlear mechanics, as first noticed by Zurek (1981) and later by Bell (1992), is also reflected by the observation that it can be modulated by heartbeat (Ren *et al.* 1995; Long and Talmadge, 1997). This may imply that subtle

alterations in mechanical properties of the cochlear transducer by operating point shifts could be a mechanism for cochlear gain control since mechanical structures with high gain may be required for SOAE formations.

Another temporal observation is the time delay in the f_{SOAE} oscillation with reference to the bias tone phase. The time delays increase with the reduction in the L_{bias} (Fig. 10). This effect is not typically observed in SOAE amplitudes because of a lack of AM at lower biasing levels. However, observations at these levels reveal a level-dependent reduction in frequency excursion or bandwidth. It can be noted that the FM time delay is inversely related to the range of f_{SOAE} oscillation. In a study of SOAE magnitude fluctuations, the relaxation or adaptation time constant is derived as the inverse of the bandwidth of the SOAE envelope which shows a low-pass characteristic (Wit, 1993). Similarly, the bandwidth of the f_{SOAE} oscillation can be determined by two factors: the rate of modulation that equals $2f_{\text{bias}}$ [Fig. 9(B)] and the Δf_{SOAE} that can be found from either the 90% range in the f_{SOAE} histogram [Fig. 9(C)] or twice the overall f_{SOAE} shift (Fig. 6, top). Thus, the delay time constant (τ) could be estimated:

$$\tau = \frac{1}{2\pi 2\sqrt{\Delta f_{\text{SOAE}} f_{\text{bias}}}}. \quad (6)$$

Given a Δf_{SOAE} ranging from 20 to 100 Hz, the delay constants vary from 3.5 to 0.8 ms from low to high biasing frequencies. These time constants are in close agreement with the observed values in Figs. 10 and 11, those for amplitudes of SOAEs (Bian and Watts, 2008), and DPOAEs (Bian *et al.*, 2004; Bian and Scherrer, 2007; Hensel *et al.*, 2007). The short-time delays are comparable with the onset delays of SOAE suppression (Schloth and Zwicker, 1983; Murphy *et al.*, 1995) and the auditory nerve responses (van der Heijden and Joris, 2005). These results may imply that a time-dependent mechanism, possibly the adaptation of hair cell transduction channels, could play a role in optimizing cochlear function and lead to the generation of SOAEs.

V. SUMMARY AND CONCLUSION

In addition to AM and suppression, low-frequency biasing of cochlear structures can shift and modulate the f_{SOAE} . The overall effect is an upward shift of the f_{SOAE} with increase in the L_{bias} . Up to 2% frequency shifts are observed depending on the relative strength of a bias tone over a particular SOAE based on the biasing frequency and level. The frequency shift usually occurs at relatively lower bias tone levels prior to the AM and suppression of the SOAE. Analyzing the f_{SOAE} at the bias tone peaks and troughs reveals a U-shaped modulation pattern which indicates that biasing in either positive or negative direction can increase the f_{SOAE} . The instantaneous f_{SOAE} over one biasing cycle demonstrates a W shape. The f_{SOAE} peaks at the biasing extremes and minimizes near the zero crossings of the bias tone with a short delay. These static and dynamic effects of the bias tone on the f_{SOAE} indicate that modifications of the mechanical properties of the hair cell transducer could likely cause the frequency shift and modulation. Periodic variation in possi-

bly the stiffness of OHC hair bundles due to biasing may imply that the regulation of cochlear transducer feedback gain is achieved by cellular actions, such as adaptations. The results suggest that the nonlinearity in cochlear transducers acting as internal reflection interfaces of an inner ear standing wave (Shera, 2003) could influence the ear-canal SOAE properties, such as amplitude stability and spread of the spectral peak width.

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APPENDIX

If a carrier signal with a frequency of f_c is frequency modulated by a low-frequency tone, the FM signal can be written as

$$s_{\text{FM}}(t) = A \sin(2\pi f_c t + I_m \sin 2\pi f_m t), \quad (\text{A1})$$

where A is the amplitude of the carrier, f_m is the modulator frequency ($f_m \ll f_c$), and I_m is the modulation index which is defined as the ratio of the frequency change or deviation (Δf) with respect to the modulation frequency, i.e.,

$$I_m = \Delta f / f_m. \quad (\text{A2})$$

Applying trigonometric identity $\sin(\alpha + \beta) = \sin \alpha \cos \beta + \cos \alpha \sin \beta$, and replacing frequencies $2\pi f_c$ and $2\pi f_m$ with their angular forms ω_c and ω_m , the FM signal in Eq. (A1) can be rewritten as

$$s_{\text{FM}}(t) = A \sin \omega_c t \cos(I_m \sin \omega_m t) + A \cos \omega_c t \sin(I_m \sin \omega_m t). \quad (\text{A3})$$

According to Bessel function identities: $\cos(x \sin \theta) = 2\sum_{n=0}^{\infty} J_n(x) \cos(n\theta)$, where n is even, and $\sin(x \sin \theta) = 2\sum_{n=1}^{\infty} (-1)^n J_n(x) \sin(n\theta)$, where n is odd, the spectral components of the FM signal around the carrier can be expressed as follows:

$$S_{\text{FM}}(f) = A \sin \omega_c t \left[2 \sum_{n=0}^{\infty} J_n(I_m) \cos(n\omega_m t) \right] + A \cos \omega_c t \left[2 \sum_{n=1}^{\infty} (-1)^n J_n(I_m) \sin(n\omega_m t) \right]. \quad (\text{A4})$$

Multiplying through, expanding the first term as $n=0$, and applying the formula $\sin \alpha \cos \beta = \frac{1}{2} \sin(\alpha \pm \beta)$ for the rest of the terms, it yields the spectral expression of the carrier and sideband components

FIG. 12. Sideband amplitudes of FM signals. As the modulation index (I_m) increases to 2, the sideband amplitudes ($J_1, J_2, \dots$) also increase. When $I_m < 1$, the amplitudes of sidebands with orders higher than 2 are negligible ($< 2\%$). Calculation is based on summing the first 15 terms of the Bessel function of the first kind in Eq. (A7). J_0 is the amplitude of the carrier, J_1 is the amplitude of sideband I, J_2 is the amplitude of sideband II, and etc.

$$S_{\text{FM}}(f) = J_0(I_m) \sin \omega_c t + \sum_{n=2}^{\infty} J_n(I_m) \sin(\omega_c \pm n\omega_m t) - \sum_{n=1}^{\infty} (-1)^n J_n(I_m) \sin(\omega_c \pm n\omega_m t). \quad (\text{A5})$$

Combining the odd and the even terms, the above equation can be written as

$$S_{\text{FM}}(f) = J_0(I_m) \sin \omega_c t + \sum_{n=1}^{\infty} J_n(I_m) \sin(\omega_c + n\omega_m)t + (-1)^n \sum_{n=1}^{\infty} J_n(I_m) \sin(\omega_c - n\omega_m)t. \quad (\text{A6})$$

The first term is the frequency component of the carrier with an amplitude of J_0 . The second and third terms contain all the components in the USBs and LSBs of the FM signal. The sidebands are distributed at integer (n) multiples of the f_m above and below the carrier. The amplitudes of the carrier and the sidebands are determined by the coefficient $J_n(I_m)$ in the form of the Bessel function of the first kind:

$$J_n(I_m) = \sum_{i=0}^{\infty} (-1)^i \frac{(I_m/2)^{2i+n}}{i! \cdot \Gamma(i+n+1)}, \quad (\text{A7})$$

where n denotes the order of the sidebands, with 0 indicating the carrier component, and Γ is a gamma function which for all positive integers is equivalent to a factorial, i.e., $\Gamma(i+n+1) = (i+n)!$. For varying I_m , the Bessel function is solved by summing 15 terms in Eq. (A7) and plotted in Fig. 12. It can be observed that when I_m is smaller than 1 which is the case of low-frequency modulation of SOAEs, the sizes of sidebands with orders higher than 2 (J_3 and J_4) are negligible and can be omitted in the spectral windowing. Therefore, the bandwidth of the FM signal can be determined as

$$B_m = 2(\Delta f + 2f_m), \quad (\text{A8})$$

where Δf is added to account for the shift of f_c due to the low-frequency biasing.

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