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Two-tone suppression of stimulus frequency otoacoustic emissions^{a)}

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Abstract

Stimulus frequency otoacoustic emissions (SFOAEs) measured using a suppressor tone in human ears are analogous to two-tone suppression responses measured mechanically and neurally in mammalian cochleae. SFOAE suppression was measured in 24 normal-hearing adults at octave frequencies ($f_p=0.5\text{--}8.0$ kHz) over a 40 dB range of probe levels (L_p). Suppressor frequencies (f_s) ranged from -2.0 to 0.7 octaves *re: f_p*, and suppressor levels ranged from just detectable suppression to full suppression. The lowest suppression thresholds occurred for “best” f_s slightly higher than f_p . SFOAE growth of suppression (GOS) had slopes close to one at frequencies much lower than best f_s , and shallow slopes near best f_s , which indicated compressive growth close to 0.3 dB/dB. Suppression tuning curves constructed from GOS functions were well defined at 1, 2, and 4 kHz, but less so at 0.5 and 8.0 kHz. Tuning was sharper at lower L_p with an equivalent rectangular bandwidth similar to that reported behaviorally for simultaneous masking. The tip-to-tail difference assessed cochlear gain, increasing with decreasing L_p and increasing f_p at the lowest L_p from 32 to 45 dB for f_p from 1 to 4 kHz. SFOAE suppression provides a noninvasive measure of the saturating nonlinearities associated with cochlear amplification on the basilar membrane.

I. INTRODUCTION

Evoked otoacoustic emissions (OAEs) provide a noninvasive tool to test theories of auditory processing at the mechanical level within the cochlea. The present study was designed to measure two-tone suppression of stimulus frequency (SF) OAE responses in normal-functioning human ears over broad ranges of probe frequency and level, and suppressor frequency and level. Motivated by the many similarities in auditory processing at the cochlear, neural and behavioral levels, the approach was to describe suppression of SFOAEs and to compare these data to previous reports of effects of suppression and simultaneous masking at other levels of auditory processing. This introduction summarizes concepts from cochlear mechanics and, to a lesser extent, psychoacoustics that are directly relevant to our analyses of SFOAEs. Such concepts include cochlear nonlinearity, two-tone suppression, rate of growth of suppression, tuning curves and their parameterization using quality factor (or Q) and tip-to-tail difference.

Many psychoacoustic models are based on functional models of basilar-membrane (BM) mechanics, in which a frequency-selective nonlinear filter is an essential component (Moore and Oxenham, 1998). As reviewed in Robles and Ruggero (2001), BM mechanics provide sharp tuning at low stimulus levels similar to that of neural tuning, and less sharp tuning at

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higher levels. Sharp tuning was explained in terms of a cochlear-amplifier mechanism (Gold, 1948; Davis, 1983), and active cochlear models having a source of internal energy show sharper tuning than passive models (Neely and Kim, 1983). The endocochlear potential serves as a source of internal energy used by outer hair cells (OHCs) to amplify low-level vibrations on the BM. OHC electromotility (Brownell *et al.*, 1985) contributes to sharp tuning, providing a cycle-by-cycle cochlear feedback amplifier that increases the motion of the BM (Mountain *et al.*, 1983).

A neural tuning curve shows the stimulus threshold sound pressure level (SPL) at the tympanic membrane producing a criterion increment above the spontaneous firing rate of an auditory-nerve fiber as a function of frequency (Liberman, 1982). Its tip region is the narrow frequency range where the threshold is lowest, and its tail region at lower frequencies is where the thresholds are elevated, but relatively constant. Its tip-to-tail difference is the threshold SPL difference between the tip and tail regions, and its quality factor, or Q , assesses frequency selectivity.

Tuning curves measured from auditory fibers, depolarization of inner hair cell (IHC) potentials, and BM motion are similar, which suggests that the IHC and auditory-nerve fibers each function as a detector of the mechanical motion of the BM. OHCs function *in vivo* in a feedback loop as bi-directional transducers from mechanical to electrical energy, and from electrical to mechanical energy to amplify the low-level motions of the BM (Patuzzi, 1996). Cochlear dysfunction that results in a reduction in endocochlear potential would reduce OHC motion, reduce cochlear amplification of low-level BM motion, and thereby reduce the depolarization of IHCs, which would result in reduced auditory-nerve firing rates. Mild and moderate sensorineural hearing losses are often due to OHC dysfunction, although more severe sensorineural hearing losses are expected to involve IHC or neural dysfunction. Animal experiments based on administration of furosemide confirm this interpretation. Furosemide reduces the endocochlear potential and elevates the thresholds of auditory-nerve fibers by large amounts in the tip region, where cochlear amplification is predominant, and by smaller amounts in the tail region, where the BM motion is more nearly linear (Sewell, 1984). Thus, the tip-to-tail difference of auditory-nerve fibers and of BM motion is reduced by furosemide (Ruggero and Rich, 1991).

Evoked OAE responses can be measured using stimulus conditions that are correlates of those used in behavioral, neural and BM studies of spectral and temporal processing. Evoked OAE types have been classified in several ways, one of which is based on generation mechanism (Kemp, 1986; Shera and Guinan, 1999). A SFOAE is a quasi-sinusoidal evoked cochlear response at a probe frequency f_p , and is thought to be generated mainly within the tonotopic region of f_p on the BM (Kemp, 1979; Wilson, 1980; Kemp and Chum, 1980; Zwicker and Schloth, 1984; Kemp and Brown, 1983a). SFOAE and click-evoked (CE)OAE are thought to be generated in human ears via a linear coherent reflection emission mechanism (Zweig and Shera, 1995; Kalluri and Shera, 2007). Distortion-product (DP) OAE (Kemp and Brown, 1983a; Harris *et al.*, 1989) are generated via a nonlinear distortion mechanism (Kemp and Brown, 1983b; Kemp, 1986). Nonlinear distortion observed in the ear canal as a DPOAE originates in the mechano-electrical transducer of the OHC, which relates the input hair-bundle displacement to the output receptor potential. This receptor-potential nonlinearity is also responsible for two-tone suppression (Weiss and Leong, 1985; Geisler *et al.*, 1990; Lukashkin and Russell, 1998). While place-fixed emissions are linear at low stimulus levels, most observations of SFOAEs occur at moderate levels at which the same cochlear nonlinearity attributed to the OHC is present.

SFOAEs are of particular interest because many auditory experiments measure: (1) the response to excitation by a tone, or (2) the detection of a tone in the presence of a “suppressor”

or “masker.” While BM and other physiologically invasive measurements in animals have proven useful in developing psychoacoustical models, these measurements are impossible to perform in humans for ethical reasons. Conversely, most psychoacoustics experiments have been performed using human listeners. SFOAEs may serve as an OAE correlate to nonlinear sinusoidal response growth at the BM, neural and behavioral levels, and thus serve as a way to link data from humans to observations made through invasive measurements in nonhuman mammals.

While cochlear nonlinearity can be assessed using single tones in BM input/output (I/O) responses, it can also be assessed using pairs of tones in suppression and intermodulation distortion responses (Ruggero and Rich, 1991; Ruggero *et al.*, 1992). Two-tone suppression has been observed in neural responses (Sachs and Kiang, 1968; Arthur *et al.*, 1971) and mechanical responses, as reviewed in Robles and Ruggero (2001). Mechanical suppression results from the saturation of the active-feedback mechanism, which leads to a more nearly linear BM I/O function (Zwicker, 1986).

Two-tone suppression of SFOAEs has been measured in cat (Guinan, 1990), chinchilla (Siegel *et al.*, 2003; Rhode, 2007), and human ears (Kemp and Chum, 1980; Brass and Kemp, 1993), in which human data were reported for three ears over a one-octave range of f_p . Two-tone suppression of SFOAEs in chinchillas was similar to responses in humans for low-frequency suppressors, but more complex for high-frequency suppressors (Siegel *et al.*, 2003). Unlike neural, mechanical, or behavioral measurements of two-tone suppression, in which the initial unsuppressed signal is directly measured, two-tone suppression of SFOAEs uses a two-step procedure. First, the total SFOAE in human ears is indirectly inferred by fully suppressing the SFOAE (Guinan *et al.*, 2003; Schairer *et al.*, 2003; Schairer and Keefe, 2005). The *total SFOAE* is the complex pressure phasor between the fully suppressed and unsuppressed conditions. Second, the tone eliciting the SFOAE is combined with a suppressor tone at a level less than that needed for full suppression. The resulting partially suppressed SFOAE is interpreted with respect to a decrement of the total SFOAE. The bandwidth of two-tone suppression of SFOAEs in human ears extends approximately 2.1 octaves about a f_p of 1 kHz at $L_p=40$ dB SPL (Backus and Guinan, Jr., 2006).

Associated with the concepts of frequency selectivity and the cochlear amplifier is the concept of cochlear gain. Aside from issues related to indirect measurements of gain (Allen and Fahey, 1992; de Boer *et al.*, 2005; Ren and Nuttall, 2006; Shera and Guinan, Jr., 2007; Shera *et al.*, 2007), cochlear gain is higher when the OHC feedback loop is functioning normally and lower when OHC dysfunction is present. Several definitions of cochlear gain are in current use (Robles and Ruggero, 2001). Assuming that BM responses to characteristic-frequency (CF) tones grow linearly at very low and very high stimulus levels, cochlear gain can be defined as the sensitivity difference at the lowest and highest levels, where sensitivity is the ratio of BM displacement to sound pressure at the tympanic membrane. A second definition is that cochlear gain is the difference between the maximum sensitivities *in vivo* and postmortem. Unfortunately, neither definition is applicable to defining cochlear gain in human ears, so that other approaches are required.

Cochlear gain has been indirectly assayed in human ears using suppression of DPOAE responses (with stimulus frequencies f_2 and $f_1 < f_2$) by a third sinusoid. Using a simplified nonlinear model of cochlear mechanics, Mills (1998) concluded that the DPOAE tip-to-tail difference, based on the level difference at the stimulus f_2 frequency and one octave lower, would be approximately proportional to the cochlear gain at f_2 . As long as even a weak DPOAE response is present, this model predicts that the suppression of such a DPOAE response may be used to infer characteristics of the underlying cochlear gain. Using human subjects with normal hearing and mild levels of hearing loss, a negative correlation of DPOAE tip-to-tail

difference with hearing loss was obtained, which explained 29–45% of the variance in thresholds at f_2 frequencies of 2, 3 and 4 kHz (Pienkowski and Kunov, 2001). This finding supports the Mills model based on the expected high prevalence of mild sensorineural hearing loss due to impaired OHC function. These results, including the tendency to explain more of the variance in thresholds at a f_2 of 4 kHz, were replicated and extended across a broader range of DPOAE stimulus and suppression parameters (Gorga *et al.*, 2002). Focusing on a f_2 of 4 kHz, the correlation of tip-to-tail difference with sensation level explained more variance than did its correlation with threshold SPL (Gorga *et al.*, 2003). Gorga *et al.* concluded that subjects with mild-to-moderate hearing loss have reduced cochlear gain compared to normal-hearing subjects, even though they have similar tuning around the tip of the DPOAE suppression tuning curve (STC). The properties of cochlear gain assessed indirectly using SFOAE STCs have not been studied.

One goal of this study was to determine the extent to which noninvasive measurements of SFOAE suppression reveal properties of cochlear processing in humans similar to knowledge gained from invasive experiments in other mammals. Another goal was to compare such measurements of SFOAE suppression to measurements of psychoacoustic masking and suppression, which have been explained using theories incorporating a compressive nonlinearity in the auditory periphery (Oxenham and Bacon, 2004). SFOAE suppression was measured based on SFOAE residual responses (SPL and phase) obtained over wide ranges of frequencies and levels of both probe and suppressor signals. From these measurements, SFOAE STCs were constructed as a function of suppressor frequency and level. Parameters of these STCs relevant to understanding cochlear nonlinearity and selectivity were analyzed, including a quality factor Q_{ERB} , which is based on the equivalent rectangular bandwidth (ERB) of the STC, the rate of the growth of suppression, cochlear compression, and the tip-to-tail difference. These measurements in individual ears were analyzed into group results and compared to published results of corresponding mechanical and neural measurements.

II. METHODS

A. Subjects

Data from subjects participating in this study were included only if their air-conduction thresholds were ≤ 15 dB at each half octave from 0.25 to 8 kHz and their air-bone gaps were ≤ 10 dB. SFOAE data were acquired in one ear of each subject on one day at a particular f_p , and data were collected at five f_p frequencies. For each f_p , the air- and bone-conduction data were collected on the same day as were the SFOAE data. A group of 24 normal-hearing subjects participated in the present study (21 females and 3 males), and data were collected in 12 right ears and 12 left ears. The age range was 20–39 years with a mean age of 28 years. The original goal was to test each of 20 subjects at all frequencies, but only 15 subjects attended all five test sessions. Additional subject recruitment was performed until 20 subjects had been tested at each of the five f_p frequencies.

B. Data collection and analysis

Data were collected using a probe assembly with two receivers and one microphone (Eytmotic ER10C, modified at the factory to allow a 20 dB increase in output from each receiver). A sound card (CardDeluxe) under computer control outputted an electrical stimulus through each of a pair of digital-to-analog converters (DACs), with the output of each DAC driving a receiver. The output response signal from the microphone was recorded using an analog-to-digital converter (ADC). These converters were part of the sound card installed in a Windows computer operating with custom software. Data were converted synchronously at a sample rate of 22.050 kHz per channel. Each sinusoidal tone was presented through a separate receiver to minimize intermodulation distortion within the probe system. The probe was inserted into the

ear canal using a soft foam tip to ensure the subject's comfort during the experiment. Acoustic pressure signals were measured at the probe tip.

The stimulus set included a presentation of a sinusoidal probe tone of frequency f_p , which was varied over a set of five octave frequencies from 0.5 to 8 kHz, a presentation of a sinusoidal suppressor tone of frequency f_s and level L_s , and the joint presentation of probe and suppressor tones. Data were acquired at each f_p for probe levels L_p ranging from 20 to 70 dB SPL in 10 dB steps. The f_s stimuli ranged from two octaves below f_p to 0.7 octaves above f_p . For example, the complete range at $f_p=1$ kHz extended from approximately 0.25 up to 1.6 kHz. The particular values of f_s/f_p for each f_p were 0.260, 0.348, 0.522, 0.609, 0.695, 0.825, 0.956, 1.043, 1.130, 1.174, 1.260, 1.347, 1.434, 1.477, and 1.61. The range was slightly reduced at the highest $f_p=8$ kHz: the maximum f_s/f_p was limited to 1.33 so that f_s would not exceed the Nyquist criterion.

The microphone response to the probe stimulus was p_p , to the suppressor stimulus was p_s , and to the joint presentation of the probe and suppressor stimuli was p_{ps} . The *SFOAE residual* was defined in terms of the nonlinear residual p_{oae} to these three stimuli by (Keefe, 1998):

$$p_{\text{oae}} = p_p + p_s - p_{ps}. \quad (1)$$

If this SFOAE residual corresponded to full suppression of the SFOAE, then this SFOAE residual would equal the total SFOAE as defined in the Introduction. The data collection and averaging procedures were similar to those described in Schairer *et al.* (2003). The low-level data acquisition procedures used to measure SFOAE residuals are further described in the Appendix.

Responses were always measured over the full range of L_p , but data were acquired over subranges of f_s and L_s that varied according to f_p and L_p . Preliminary test data were used to identify these subranges, based on the premise that data need not be acquired if no SFOAE residual would be detected. The choices of subranges were checked after all data in the present study were acquired. The range of L_s did not exceed 20–92 dB SPL at $f_p=0.5$ kHz or 14–80 dB SPL for $f_p>0.5$ kHz. The L_s was varied in 6 dB steps.

Data were collected while the subject was comfortably seated in a sound-attenuated room. The number and range of parameter values was constrained by the practical limitation of a nominal 2 h duration for each f_p , which included a break in the middle. Data were collected for each subject over five separate sessions, with each session on a different day. It was never the case that the subrange was too restricted to measure a low-level SFOAE residual. The only restriction that was encountered occurred at $f_p=4$ kHz, for which the maximum L_s of 82 dB SPL was too low. This is further described in the Discussion.

For each L_p and f_p , a SFOAE residual was judged valid at each f_s and L_s only if each of the following was satisfied: (1) its signal to noise ratio (SNR) was at least 6 dB, (2) its noise SPL at each f_s and L_s did not exceed the median noise SPL (at that f_s and across its L_s range) by more than 6 dB for any L_s , and (3) its noise SPL at each f_s and L_s remained within 10 dB of the grand median noise SPL calculated across both L_s and f_s . Condition 2 was intended to exclude intermittent noise. Condition 3 ensured that intermittent noise spikes for individual f_s suppressors were excluded, so that the construction of the STC curve was not contaminated by such artifact. It was not surprising that some subject-generated artifacts occurred in an experimental session lasting 2 h, and the above objective criteria were helpful in excluding such artifacts.

The biological origin of the SFOAE residual was confirmed by comparisons with recordings in an artificial ear (IEC 711 reference coupler, Bruel & Kjaer Type 4157). SFOAE residuals were not measured at $f_p=0.5$ kHz for $L_p<40$ dB SPL because preliminary studies showed that

the SNR was too small at lower levels. Coupler distortion was present at 8 kHz in the range of some of the biological responses, and especially at the highest L_p of 70 dB SPL. Thus, the range of probe levels in the analyzed results was restricted to 20–60 dB SPL.

III. RESULTS

The individual-ear responses plotted below were selected from recordings in several subjects so that the variety and overall consistency of responses can be appreciated. An example of SFOAE residual SPLs for an individual ear (subject 1) is shown in Fig. 1 for a SFOAE at $f_p=1$ kHz as a function of f_s and L_s . Each row shows data at increasing L_p levels from 20 to 60 dB SPL in 10 dB steps. Each SFOAE residual SPL curve is plotted versus L_s (solid lines), and the corresponding noise SPL is shown as a dashed line of the same thickness. The left column of panels show data for low-side suppressors $f_s < f_p$ and the right column for high-side suppressors $f_s > f_p$. Only those SFOAE residuals with a 6 dB SNR are plotted, except that the SPL is also shown for the next lower value of L_s that did not satisfy this SNR criterion so that the shape of the curve emerging from the noise floor is evident. Only a few of the suppressor frequencies produced sufficiently high SPLs at low L_p , e.g., see data for $L_p=20$ dB SPL. This occurred because the SFOAE level had insufficient dynamic range relative to the noise level.

At $L_p=40$ and 50 dB SPL, the SFOAE residual curves were well defined for many of the suppressors. Low-side SFOAE suppression was characterized by a relatively steep slope (>1 dB/dB) that was nearly constant across f_s . High-side SFOAE suppression was characterized by a similarly steep slope for f_s just above f_p , but smaller slopes (<1 dB/dB) for higher f_s . These slopes are further described below (see Fig. 8). The saturation region (identified by a horizontal line in each panel) was well defined for $L_p > 20$ dB SPL. The maximum residual SPL in the saturation region was the total SPL of the SFOAE (corresponding to full suppression of the SFOAE), and in this example was 13 dB SPL at $L_p=40$ dB SPL and 18 dB SPL at $L_p=50$ dB SPL. These total SFOAE SPLs are not plotted inasmuch as they were consistent with previous reports based on I/O functions (Schairer *et al.*, 2003; Schairer and Keefe, 2005). The saturation region was poorly defined at $L_p=20$ dB SPL because the SNR was small, as noted above. In such cases, the saturation region was defined as the maximum SFOAE residual SPL with a slope not exceeding 0.12 dB/dB, which ensured that the region so defined had a shallow slope consistent with a saturation effect. A typical high-side suppression pattern showed incomplete suppression of the SFOAE at the highest f_s (i.e., the thin lines for L_p of 40 and 50 dB in Fig. 1), inasmuch as their residual SPLs were smaller than those measured at lower f_s . This is because the L_s levels used for these high-side suppressors were insufficient to completely suppress the SFOAEs.

For a specific probe condition parametrized by f_p and L_p , the SFOAE STC was the set of L_s values that produced iso suppression, i.e., the same SFOAE residual SPL, as a function of f_s . The SFOAE STC at each f_s was constructed using a cubic-spline interpolation of the data in Fig. 1 to calculate the L_s for which the SFOAE residual SPL was 10.7 dB below the total SPL. This criterion is shown by the horizontal dotted line that is 10.7 dB below the total SPL (horizontal solid line) in each panel of Fig. 1. This criterion SPL is defined as the *SFOAE decrement* and is measured relative to the SPL of the total SFOAE. SFOAE suppression of the probe tone produced a decrement at f_p . This decrement was observed as an increment in the SFOAE residual; i.e., no SFOAE residual meant no suppression of the SFOAE.

A 3 dB increment in the SFOAE residual corresponded to an amplitude increase by a factor of $1/\sqrt{2}$. This 3 dB increment was equivalent to a 10.7 dB decrement with respect to the SPL of the total SFOAE, because $20 \log_{10}(1 - 1/\sqrt{2}) = -10.7$ dB. STCs were also constructed using an alternative criterion decrement of 6 dB to study the effect of varying the criterion. A 6 dB decrement in the SFOAE residual was equivalent to a 6 dB decrement with respect to the SPL

of the total SFOAE, because -6 dB corresponds to an amplitude change of $1/2$ and $20 \log_{10}(1-1/2) = -6$ dB. The criterion of 10.7 dB was preferred for constructing a SFOAE STC, because it was closer to the onset-of-suppression threshold. STCs constructed using the alternative criterion of 6 dB were sufficiently similar to those constructed using the 10.7 dB criterion that results are reported only using the 10.7 dB criterion.

The SFOAE residual data had to be valid (as described in Sec. II) for at least 70% of the f_s frequencies in order to calculate a STC. The data in Fig. 1 illustrate that interpretable SFOAE STCs would be constructed for L_p at and above 30 dB SPL, but not at 20 dB SPL because of an insufficient number of valid data (mainly due to the low SNR at $L_p = 20$ dB SPL).

The SFOAE residual plots showed evidence at 0.5 kHz in more than half of the ears of a high-level region above the saturation region, in which the SFOAE SPL residual increased rapidly with L_s . Although the example in Fig. 2 (subject 15) showed a well-defined saturation region for low-side suppression (left column), an additional high-level region for L_s above 80 – 86 dB SPL was present for high-side suppression when $L_p = 50$ dB SPL. Such a rapid increase in the SFOAE SPL residual is not predicted by the two-tone suppression mechanism. This was probably not a middle-ear muscle reflex effect because it was present only for high-side suppression. Any reflex effect elicited by a suppressor f_s slightly larger than f_p would also have been elicited by a suppressor slightly smaller than f_p . It was likely a cochlear-distortion effect acting near the tonotopic location of f_s and slightly basal to the f_p place. A possible mechanism for such distortion has been described by Talmadge *et al.* (2000). This increase was also observed on low-side suppression in a few ears (not shown), for which an activation of the middle-ear muscle reflex by a high-level suppressor was a possibility.

The SFOAE residual at $f_p = 4$ kHz for subject 5 in the left column of Fig. 3 shows the SFOAE SPL at fixed L_p as a function of f_s/f_p , with each curve plotted at fixed L_s . High-side suppression dominated at low L_s , with a most sensitive region approximately one-quarter octave above f_p ($f_s/f_p \approx 1.19$) for L_p in the range from 20 to 50 dB SPL. The most sensitive region increased to $f_s/f_p = 1.6$ at $L_p = 60$ dB SPL, a trend also evident in the STC at $L_p = 50$ dB SPL. Saturation of the SFOAE residual occurred at high L_s , and the STC broadened towards lower f_s/f_p at higher L_s . As expected, the maximum suppression, when saturated, was independent of L_s and f_s , but varied with L_p , because it depended on the probe response alone.

An alternative representation of the SFOAE residual SPL is in terms of a SFOAE suppression sensitivity function. This is defined as the amplitude ratio of the SFOAE pressure residual (produced by the suppressor) to the suppressor pressure. When expressed as a level, the suppression sensitivity level is the difference of the SFOAE residual SPL relative to L_s . This is plotted as a function of f_s/f_p in the right column of Fig. 3, such that each curve is an iso-suppressor response at a particular L_s . Either representation shows that SFOAE suppression is most sensitive at low levels for $f_s/f_p > 1$. The suppression sensitivity level shows the increasing breadth of the suppression peak with increasing L_s as a function of f_s/f_p . The panels with $L_p = 50$ dB show one case of artifact when f_s was close to 0.125 kHz, which lies below the minimum frequency plotted. The maximum suppression sensitivity levels in Fig. 3 ranged from -25 dB at low L_p to -33 dB at high L_p .

The altered shape of the suppression sensitivity at a L_p of 50 – 60 dB SPL is an indicator that cochlear nonlinearity is qualitatively changing in this moderate range. The peak sensitivity shifted to slightly higher f_s/f_p at high L_p . The shift appeared discontinuous inasmuch as the sensitivity at $L_p = 50$ dB had two peaks, one similar to the single-peak frequency at $L_p = 40$ dB and the other at higher f_s similar to the single-peak frequency at $L_p = 60$ dB. One possibility is that this change is related to an onset of distortion at higher L_s that occurs at f_s/f_p close to 1.5 ,

or just outside the region of cochlear-amplification around the tonotopic place. More study is needed to understand the underlying reasons for this effect.

The shape of the SFOAE suppression sensitivity somewhat resembles the vibration sensitivity (velocity per unit pressure) reported for mechanical measurements on the BM of a mammalian cochlea (Ruggero *et al.*, 1992), inasmuch as both transfer functions reveal the frequency selectivity associated with the cochlear-amplifier function of a healthy cochlea. Nevertheless, the pair of sensitivity functions are defined in terms of different variables: the input variable to the SFOAE sensitivity transfer function is the suppressor SPL at each suppressor frequency, whereas that for the vibration sensitivity at a particular location on the BM is the stimulus SPL.

The corresponding SFOAE phase suppression plot (SFOAE phase measured relative to the probe phase) is shown in Fig. 4. Each panel shows results for a single L_p , which increases from top to bottom in the figure. The individual curves show the response for a particular L_s , with increasing line thickness representing increasing L_s in 6 dB steps. SFOAE phase suppression was usually small, i.e., close to 0 periods. More phase variation was observed at $L_p=60$ dB SPL than at lower L_p . Averaged across all low-side suppressors, the average SFOAE phase lagged by approximately 0.15 periods (5°).

A SFOAE STC constructed from SFOAE residual data (such as those shown in Fig. 1 and Fig. 2) is shown for subject 23 in Fig. 5. The SFOAE STC was first measured (A, top five panels) and re-measured 30 days later (B, bottom five panels). Each panel shows the STC at an octave f_p from 0.5 to 8 kHz, with increasing line thickness representing increasing L_p . The absence of a curve at a particular L_p means that a valid STC was not obtained. Tuning in individual ears was better represented at 1, 2 and 4 kHz than at 0.5 or 8 kHz. Nevertheless, a tip region was present at most f_p . The mean and standard deviation (SD) of the difference of the first STC relative to the second STC was calculated at each f_p , by averaging over all f_s/f_p and all L_s common to both STCs. The mean difference in suppression thresholds varied from -1.7 to 5.6 dB with f_p , with a grand average of 0.6 dB. The SD of the difference varied from 6.0 to 8.7 dB with f_p , and was characterized by similar suppression thresholds for most data with a few outliers increasing the SD. Thus, the SFOAE STC of an individual ear was repeatable to within 0.6 dB overall.

Group STC responses were analyzed by averaging the SFOAE SPL and phase STCs across subjects. The SFOAE STC mean and standard error of the mean (SE) are plotted in Fig. 6. The mean STC had a tip region of maximum sensitivity at a frequency slightly higher than f_p ($f_s/f_p \approx 1.19$), which agrees with the observations of Brass and Kemp (1993). For $L_p \geq 30$ dB SPL, the tip L_s typically increased with increasing L_p . This effect is combined in the figure with the effect of shifts with increasing L_p in the most sensitive f_s . The mean and SE of the SFOAE phase STC are plotted in Fig. 7. The phase varied within ± 0.3 cycles with variations in f_s/f_p and L_p .

IV. DISCUSSION

Properties of SFOAE suppression responses are described and compared to measured mechanical and neural responses, beginning with the mean rate of growth of suppression.

A. Rate of growth of suppression

The mean rate of growth of SFOAE suppression is the increase in the SPL of the SFOAE residual for an increase in L_s . It was measured at each f_s on the STC using a SFOAE residual suppression function such as that shown in Fig. 1. For each curve parametrized by f_s , the rate of growth of suppression was calculated as the slope of this function at the intersection of the SPL that was $\Delta L=10$ dB down from the SPL of the total SFOAE. This is illustrated by the

slopes of the SFOAE residual responses plotted in Fig. 1 and Fig. 2 at a level 10 dB below the dotted line indicating full suppression (i.e., the SPL of the total SFOAE). The slope was calculated from the derivative of the spline fit. The resulting group mean and SE of the rate of growth of suppression are shown in Fig. 8.

The SFOAE rate of growth of suppression was approximately 1.5 dB/dB for low-side suppression. This compares well with measurements reported in mammalian ears at the mechanical and neural level. For example, the rate of growth of two-tone suppression in BM mechanical responses in chinchilla ranged from 0.65 to 1.42 dB/dB, with a mean of 0.97 dB/dB (Ruggero *et al.*, 1992) for suppressor frequencies below the probe frequency, when measured at a characteristic frequency (CF) place close to the probe frequency. Another study on two-tone suppression in chinchilla in the 6 kHz region showed a rate of growth of suppression on the BM larger than 2.5 dB/dB for low-frequency suppressors, which decreased with increasing suppressor frequency to less than 1 dB/dB above the characteristic frequency (Rhode, 2007). Based on measurements of two-tone suppression in auditory-nerve fibers in cat, Delgutte (1990) found that the rate of growth of suppression varied from 1 to 3 dB/dB for low-side suppression. Rhode (2007) concluded that rate of growth of suppression produced by low-frequency suppressors was similar for BM and auditory-nerve measurements in mammalian ears.

For high-side suppression at the lowest L_p levels and independent of f_p , the SFOAE rate of growth of suppression decreased with increasing f_s/f_p to approximately 1 dB/dB at $f_s/f_p=1$, and 0.3 dB/dB at the largest $f_s/f_p=1.7$. In chinchilla BM measurements, the rate of growth of suppression in two individual ears ranged from 0.30 to 0.35 dB/dB near the CF place for f_s/f_p of 1.23 and 1.25, based on f_p of 8.6 and 8 kHz, respectively (Ruggero *et al.*, 1992). In the auditory-nerve fiber measurements in cat, the rate of growth of suppression ranged between 0.15 and 0.7 dB/dB for high-side suppressors (Delgutte, 1990). Both the SFOAE and neural growth rates decreased with increasing f_s/f_p for high-side suppression.

The fact that low-side suppression growth rates were occasionally higher in neural than BM mechanical measurements, and the fact that the growth rates were slightly higher in SFOAE than BM mechanical measurements may reflect species differences, a reduction in the BM growth rate due to effects of surgery, or intrinsic differences in measurement techniques. For the latter, the mechanical BM and neural measurements are related to the motion over a particular place in the cochlea whereas the SFOAE is thought to include contributions over the breadth of the tuning around the tonotopic place of f_p . The low-side suppression growth rate based on SFOAE measurements may underestimate the non-linear compression of the cochlear amplifier because SFOAE results from a superposition of excitations over locations along the BM for which the cochlear amplification is less than near the CF place. Aside from slight differences in magnitude, however, the qualitative pattern of two-tone suppression is similar in mechanical, neural and SFOAE measurements.

B. Suppression tuning via Q_{ERB}

The frequency selectivity of suppression tuning was assessed in terms of a quality factor Q_{ERB} of each STC. The STC was inverted and its level converted to squared amplitude. At each f_p , the area under the inverted squared-amplitude function was calculated over the range of f_s , and the ERB was calculated as the ratio of this area to the peak squared amplitude at the tip of the original STC. The Q_{ERB} was calculated as $Q_{\text{ERB}}=f_p/\text{ERB}$. Each group mean ± 1 SE was calculated based on the set of individual Q_{ERB} at each f_p and L_p , and plotted in Fig. 9. However, an individual Q_{ERB} response was excluded if the tip value occurred at the highest f_s for which data were otherwise valid. This excluded STCs lacking a well-defined tip region. An example of such an excluded STC is that at $L_p=60$ dB SPL and $f_p=0.5$ kHz in Fig. 5, for which the minimum L_s occurred at the highest f_s .

The Q_{ERB} varied little with L_p , and was approximately equal to the behavioral Q_{ERB} derived from psychophysical measurements of critical bandwidth based on simultaneous masking (Glasberg and Moore, 1990). These psychophysical measurements are also shown in Fig. 9 and include both excitation and suppression effects. The approximate equivalence of Q_{ERB} in SFOAE and psychophysical measurements suggests that excitation effects in simultaneous masking may not add significant differences to the critical bandwidths accounted for by suppression effects measured acoustically. This is consistent with Oxenham and Plack (1998), who concluded that suppression plays a major role in the nonlinear upward spread of simultaneous masking for low-side maskers.

Figure 9 also shows Q_{ERB} estimated from SFOAE latencies for $L_p=40$ dB SPL, which is based on a proposed equivalence of BM latency and tuning via an assumption of cochlear scaling (Sera *et al.*, 2002). It has been suggested that this derived estimate of Q_{ERB} is similar to Q_{ERB} measured psychoacoustically using a forward-masking procedure with a low-level probe (Sera *et al.*, 2002; Oxenham and Sera, 2003). Schairer *et al.* (2006) reported SFOAE latencies at $L_p=40$ dB SPL that were similar at 1 kHz but shorter at 2 and 4 kHz compared to results in Sera *et al.*, which would suggest a smaller derived Q_{ERB} at 2 and 4 kHz. The discrepancy is currently unresolved. Schairer *et al.* also reported that SFOAE latency decreased with increasing L_p in the range from 40 to 70 dB SPL, which suggests a decrease in the derived Q_{ERB} with increasing L_p . Thus, the SFOAE-derived Q_{ERB} would approach the simultaneous-masking measurement of Q_{ERB} from above, and would also approach the present measurements of Q_{ERB} based on SFOAE suppression. It is interesting that the present Q_{ERB} results have no systematic variation with changes in L_p , whereas the SFOAE-latency derived Q_{ERB} decrease with increasing L_p . This is evidence that the SFOAE suppression and latency measures assess different attributes of the underlying BM mechanics. The present estimates of Q_{ERB} based on SFOAE suppression were similar to those associated with behavioral simultaneous masking, but lower than those associated with behavioral forward masking.

C. On-frequency and off-frequency SFOAE suppression

The SFOAE suppression thresholds L_s are plotted in Fig. 10 as a function of L_p for on-frequency (dashed lines) and off-frequency (solid lines) suppressors. This is termed a growth of suppression (GOS) response. The on-frequency GOS response represents the threshold L_s required when f_s was slightly higher (by 2–3%) than f_p , depending on the specific spectral bin frequencies available. With f_s close to f_p , the BM response is compressed by approximately the same amount at probe and suppressor frequencies, which means that the slope of the on-frequency GOS responses should be approximately 1 dB/dB. The off-frequency GOS response is the L_s required when f_s was one octave below f_p . This suppressor frequency was chosen because the entire excitation pattern at f_p is basal to the active region of the excitation pattern at f_s an octave below f_p . The BM response at the tonotopic place of f_p responds linearly to a unit growth in the off-frequency suppressor an octave below f_p , and this is taken as a criterion amount of suppression in the probe tone at f_p . Thus, a larger than unit growth in the on-frequency suppressor is required to produce the same criterion amount of suppression in the probe tone at f_p . For example, if the compressive slope c of the BM I/O function at f_p were $c = 0.25$ dB/dB, then the on-frequency suppressor would need to be increased by $1/c=4$ dB to produce the same amount of suppression as the off-frequency suppressor would produce with an increase of 1 dB.

In order to apply this BM mechanical theory to SFOAE suppression, one needs the additional assumption, which is consistent with interpretations of SFOAE latency measurements and confirmed by SFOAE residual phase data described below, that SFOAEs are predominantly generated in the tonotopic region of the probe at f_p for the range of f_s and L_s used in the present experiments. To the extent that the BM compression is uniform over the tonotopic region, then

SFOAE measurements can reveal the underlying saturating compressive nonlinearity of BM mechanics. If BM compression is nonuniform, then it is likely that the SFOAE GOS technique will underestimate the amount of compression.

The GOS results in Fig. 10 show individual-ear results with valid data as well as the group mean ± 1 SE of the threshold L_s . The on-frequency GOS response extends to low threshold values of L_s and has a slope close to one. The off-frequency GOS response is limited to relatively high threshold values of L_s and has a slope much less than one, consistent with the above model of compressive nonlinearity. The off-frequency GOS response at $f_p=4$ kHz has a ceiling effect inasmuch as most ears did not have a threshold L_s within the measurement range (≤ 80 dB SPL). This ceiling effect had only slight impact on the results at L_p of 30–40 dB SPL. The GOS responses at $f_p=4$ kHz also included a few unexpected individual-ear responses with negative slopes, which may be a result of artifact, but the overall mean appears reasonable.

The slope of each individual-ear GOS response was calculated over its range of valid data. Because these data based on responses in Fig. 10 were somewhat noisy, the median and interquartile range of the slopes of the individual GOS responses were calculated (as an alternative to the mean and SE), and are plotted in Fig. 11. The on-frequency median slope was close to 1 dB/dB for $f_p=1, 2, 4$ and 8 kHz. The on-frequency median slope was close to 1.2 dB/dB and more variable at $f_p=0.5$ kHz, most likely due to fewer valid data at 0.5 kHz and perhaps the higher noise levels accompanying measurements at this frequency. The off-frequency median slope ranged from 0.2 to 0.4 dB/dB, except that it was 0.1 dB/dB at $f_p=4$ kHz. This latter result does not indicate more compression at 4 kHz, but, rather, is a result of the ceiling effect apparent in Fig. 10 at 4 kHz. The equivalent BM compression is defined as the ratio of the off-frequency to the on-frequency GOS slopes. Because the on-frequency GOS slope was usually close to 1 dB/dB (i.e., for $f_p \geq 1$ kHz), the equivalent BM compression was approximately equal to the off-frequency GOS slope. This compression is plotted in Fig. 11 along with its numerical values at f_p other than 4 kHz. The equivalent BM compression was approximately 0.3 dB/dB at 1–2 kHz, but large variability in individual responses precluded a detailed comparison across f_p . This slope is typical of compression measured psychophysically, as summarized in Yasin and Plack (2007), but slightly larger (i.e., less compressive) than the range of 0.13–0.16 Db/dB in BM mechanical measurements Yates *et al.*, 1990; Ruggero *et al.*, 1992).

Regarding slopes estimated in other OAE studies, the compression inferred from suppression of DPOAEs at $f_2=4$ kHz was 0.26 dB/dB (Gorga *et al.*, 2002), as compared to 0.3 dB/dB in the present study at 1 and 2 kHz. The slope of the SFOAE I/O function, which is the slope of the total SFOAE SPL as a function of L_p , is compressive with values in the range of 0.44–0.61 dB/dB between f_p of 1–4 kHz (Schairer *et al.*, 2003). These slopes are higher than the present slopes obtained from GOS data. Along with the presence of notches in SFOAE I/O functions (Schairer *et al.*, 2003; Schairer and Keefe, 2005), these data suggest that the SFOAE I/O function is not simply related to the BM I/O function.

In contrast, using a method originally described in Epstein *et al.* (2004), Epstein and Florentine (2005) reported a mean slope of click-evoked (CE) OAE and tone-burst evoked (TB) OAE I/O functions of 0.19 dB/dB in human ears near 1 kHz, which they concluded were similar to slopes of the underlying BM I/O function. CEOAEs and SFOAEs are thought to be generated by the same underlying mechanism in the human cochlea (Konrad-Martin and Keefe, 2003, 2005; Kalluri and Shera, 2007), so that the difference between the OAE I/O function slopes (0.19 and 0.44–0.61, respectively) is problematical. Epstein *et al.* (2004) stated that the TBOAE was “measured within a 21.48 ms window beginning 13–20 ms after the onset of the tone burst.” However, the SFOAE (and thus CEOAE or TBOAE) delay at 1 kHz is approximately 11 ms at low levels, and decreases with increasing stimulus level (Schairer *et al.*, 2006). Thus, it would appear that the onsets of windows used by Epstein *et al.* were later than the latency

of the CEOAE energy, so that most of the OAE energy occurred prior to the window onset. Since latency decreases with increasing stimulus level, proportionally less of the TBOAE energy would have been contained within their analysis window at higher stimulus levels. That might explain why their reported I/O function slope was so small. The present compressive slope derived from on-frequency and off-frequency GOS appears more closely related to the underlying BM mechanics.

D. Tip-to-tail difference of the STC and cochlear gain

The tip-to-tail difference of each SFOAE STC was calculated as the level difference between the on-frequency GOS threshold relative to the off-frequency GOS threshold at each f_p . The resulting group mean ± 1 SE of the tip-to-tail difference is plotted in Fig. 12. Tip-to-tail differences decreased with increasing L_p at each f_p , as expected from cochlear-amplifier theory. At the lower L_p 's (30–40 dB SPL) for which the active mechanism is strongest, the tip-to-tail differences increased with increasing f_p from 1 to 4 kHz. At the lowest $L_p=30$ dB SPL, the mean tip-to-tail difference increased from 32 dB at 1 kHz to 45 dB at 4 kHz. The tip-to-tail differences at $f_p=4$ kHz at $L_p \geq 40$ dB SPL were underestimated due to the ceiling effect illustrated in Fig. 10, so that the conclusion derived from Fig. 12 that cochlear gain is higher at 4 kHz than other frequencies is further strengthened. The tip-to-tail differences at $f_p=0.5$ kHz were difficult to interpret because of higher variability. The tip-to-tail differences at 8 kHz appeared reduced relative to results at 4 kHz at L_p of 50 and 60 dB SPL. These 8 kHz data are further discussed below.

Two-tone suppression processes at the BM and neural levels have been explained by a positive feedback process that is linear at low stimulus levels and saturates at high stimulus levels (Zwicker, 1979). In particular, the saturating nonlinearity of OHC receptor currents as a stage in mechano-electrical transduction is mainly responsible for two-tone suppression in the mammalian cochlea (Geisler *et al.*, 1990). Full saturation of this nonlinearity at high suppressor levels results in a passive, or unity-gain, cochlea. A simple model of a saturating nonlinear growth of cochlear response is shown in Fig. 13 by the solid gray curve, such that the input and output levels (in dB) are scaled in arbitrary units. The plot represents the BM input/output (I/O) function recorded at the best-frequency place of the input probe tone. The I/O function has linear growth at low input levels, compressive growth at moderate levels, and linear growth at input levels sufficiently high that the active gain mechanism has saturated. The onset of compressive growth in this example occurs at an input level of 30 dB. The corresponding BM I/O function for a passive cochlea, i.e., one without the active mechanism providing gain at low levels, is shown by the dashed curve in Fig. 13. The horizontal level difference between the low-level linear-growth region of the active model and passive model is one definition of cochlear gain described earlier. The cochlear gain in this example is 40 dB.

In the two-tone suppression model of Geisler *et al.*, the active cochlear response in the absence of suppression is represented by the solid gray curve, and the fully suppressed cochlear response is represented by the dashed gray curve. Because the passive I/O function has a slope of one, the cochlear gain may be measured equally well by the vertical level difference between the active and passive I/O functions at an input level for which the active cochlear model is in the low-level linear-growth regime. This is shown in Fig. 13 by the output level difference at an input level of 20 dB, for which the cochlear gain is again 40 dB. When these I/O functions are compared at the input level corresponding to the onset of compression (30 dB input level in this example), the vertical level difference is 38 dB. Thus, the level difference between the unsuppressed and fully suppressed cochlear responses at the onset of compression is a slight underestimate of cochlear gain.

Suppose that the unsuppressed and fully suppressed responses are measured over a limited range of input levels from 30 to 60 dB, as shown by the black lines in Fig. 13. The unsuppressed

and fully suppressed model responses are similar to the off-frequency and on-frequency GOS responses, respectively, in Fig. 10. The link between this model of BM nonlinearity and the present SFOAE measurements is the hypothesis that the SFOAE at f_p is generated as a result of two-tone suppression near the tonotopic place of f_p . The tip-to-tail difference in the SFOAE suppression response thus serves as a conservative measure of cochlear gain because the tip-to-tail difference is analogous to the vertical difference in I/O functions at the onset of compression.

The ceiling effect at $f_p=4$ kHz (see Fig. 10) means that tip-to-tail differences at $L_p \geq 40$ dB SPL were likely even larger than those shown in Fig. 12 (at $f_p=4$ kHz). This suggests that the cochlear gains were also larger in these stimulus conditions. While data are limited at $f_p=8$ kHz to higher L_p levels, it appears that the tip-to-tail differences and, thus, the cochlear gain is reduced at 8 kHz compared to 4 kHz.

Our results suggest that cochlear-amplifier gain in the human cochlea increases with increasing f_p in the range from 1 to 4 kHz. This is qualitatively similar to single-unit neural data described in the Introduction. This frequency trend was present for higher L_p of 50 and 60 dB SPL, but possibly not at $L_p=70$ dB SPL. The tip-to-tail difference was reduced at 8 kHz for L_p of 50 and 60 dB SPL, but there is lower confidence in these data because of increased measurement-system distortion at 8 kHz. For example, in Fig. 10, the slope of the off-frequency GOS responses was negative, indicative of an artifact such as distortion or intermittent noise, in a larger proportion of individual ears at $f_p=8$ kHz than at lower f_p . Of course, the absolute number of individual ears with valid data at $f_p=8$ kHz was also small.

Relative to the tail region where the BM mechanics are linear, the fact that the greatest amount of suppression near the tip occurred at the lowest L_p levels is consistent with BM mechanical measurements in chinchilla (Ruggero *et al.*, 1992) and in neural measurements in cat (Delgutte, 1990). The maximum tip-to-tail ratios in the neural measurements were approximately 40–50 dB as compared to a range of 30–45 dB in the SFOAE measurements at the lowest $L_p=30$ dB SPL. This relation between two-tone suppression and cochlear gain has also been used to account for growth-of-masking responses in auditory-nerve fibers in cat (Pang and Guinan, 1997). The mean tip-to-tail difference in studies of DPOAE suppression in human ears lies in the range of 42–45 dB at a stimulus frequency f_2 of 4 kHz and stimulus level of $L_2=20$ dB SPL (Gorga *et al.*, 2002, 2003), which is similar to the present mean measurement of 45 dB at $f_p=4$ kHz.

As stated earlier, results were reported using a SFOAE decrement criterion of 10.7 dB, but were also analyzed using a decrement criterion of 6 dB, which corresponded to a greater amount of suppression. The resulting STCs generated using the two criteria were qualitatively similar, and the quantitative differences were in the expected directions. Using the decrement criterion of 6 dB, the STC tip was slightly elevated (i.e., larger L_s) and the tip-to-tail difference was slightly smaller. For example, the tip-to-tail difference was, on average, 2.3 dB higher across frequency and level using the decrement criterion of 10.7 dB than for the criterion of 6 dB. At the lowest probe level (30 dB SPL) for which there were data using both criteria, the tip-to-tail difference was 3.4 dB higher with the 10.7 dB criterion. It was possible to measure the tip-to-tail difference at L_p of 20 dB SPL for f_p of 2 and 4 kHz, but only using the 6 dB decrement criterion. These tip-to-tail differences were 41 dB at 2 kHz, and 47 dB at 4 kHz. This overall pattern of results was consistent with suppression acting in the tonotopic region of the probe tone at f_p .

E. Low-frequency slope of SFOAE STCs

Brass and Kemp (1993) predicted that the inverse of the SFOAE STC at low-side suppression frequencies was approximately equal to the traveling-wave envelope shape on the BM. This

was based on the assumption that most of the low-side suppression occurred near the peak of the traveling-wave envelope and that the traveling wave had an approximately constant shape over the range of f_s . The long-wavelength theory of cochlear mechanics predicts that the traveling-wave envelope increases at 6 dB/octave at low frequencies (Lighthill, 1991). A previous analysis of SFOAE STCs showed a steeper traveling-wave envelope than 6 dB/octave, but the lowest f_s was only 0.6 octaves below f_p (Brass and Kemp, 1993). Brass and Kemp commented that f_s would need to be lower, probably so that the f_s peak would lie outside the region of cochlear amplification near the f_p place.

The results of the present study included SFOAE STC data at lower f_s/f_p than in the study of Brass and Kemp, which enabled an examination of this method to estimate the traveling-wave envelope. The low-frequency tail of the SFOAE STC was selected for each subject for f_s/f_p in the range from 0.25 up to 0.61. The upper cutoff at 0.61 was to exclude f_s values close to the tip region of the STC. The STC was averaged over the low-side suppressor range, with the restriction that individual STCs asymptoting at the highest L_s were excluded. The need for such exclusion is evident at 4 kHz in individual STCs (e.g., the STC in Fig. 5) and at f_p of 0.5 kHz in the mean STC (e.g., Fig. 6), because the resulting slope would otherwise be zero. Restricting attention to $f_p < 4$ kHz, the slopes at $f_p = 0.5, 1$ and 2 kHz were all in the range of 5–7 dB/dB for moderate L_p values of 40–50 dB SPL. These results support the hypothesis that the inverse of the STC at low-side suppression frequencies is approximately equal to the traveling-wave envelope shape (Brass and Kemp, 1993). A confounding factor is the frequency dependence of middle-ear transmission, which would be expected to produce deviations from this prediction.

F. SFOAE STC phase effects

In mechanical BM measurements in chinchilla, Ruggero *et al.* (1992) reported “small-to-moderate” phase lags of above-CF suppressors relative to the probe near CF as a function of increasing suppressor level. A constant SFOAE phase in Fig. 7 means that the latency of the suppressed SFOAE was approximately independent of f_s . The variability in the SFOAE phase was larger for high-side than low-side suppressors, and no particular level effect was observed. This is evidence that the place of generation of the SFOAE residual did not vary as f_s varied, and supports the hypothesis that the SFOAE residual was generated on the BM in the region of the tonotopic place of f_p . For the purposes of the present study, this is an important finding because this lack of variation was assumed to establish a link between SFOAE tip-to-tail difference and the gain of the cochlear amplifier.

This constant SFOAE phase is similar to low-side SFOAE suppression measured in a cat (Guinan, 1990). The high-side SFOAE suppression in cat showed that SFOAE phase varied rapidly, e.g., by 1.5 periods as f_s varied over one octave (for $f_p = 1.5$ kHz, $L_p = 41$ dB SPL, $L_s = 60$ dB SPL). Guinan interpreted this rapid phase variation as associated with SFOAE components at f_p originating from the cochlear region tuned to f_s . These responses in cat were measured up to $f_s/f_p = 6.7$, whereas the present human measurements were limited to $f_s/f_p \leq 1.6$.

Our mean SFOAE STC phase responses were approximately constant to within the SEs shown in Fig. 7, but the trends showed more variation for high-side suppressors. For example, at $f_p = 4$ kHz, the SFOAE STC phase was slightly negative at lower L_p and slightly positive at higher L_p . The individual-ear SFOAE residual phase responses plotted in each panel of Fig. 4 for particular values of L_s had increased variability at the largest f_s/f_p values at the highest L_p of 50–60 dB SPL.

The discrete change in phase slope in the Guinan cat data near f_s/f_p of 1.3–1.4 suggests a transition between a two-tone suppression mechanism acting near the f_p place on the BM at lower f_s and an alternative distortion mechanism acting near the f_s place, e.g., the mechanism

described by Talmadge *et al.* (2000). When such a distortion mechanism is present, the labeling of responses as *probe* and *suppressor* is incomplete and possibly misleading. It is possible that such an alternative mechanism may have influenced our human data at the highest f_s/f_p values, but the interpretation of the SFOAE phase data was limited by a relatively small SNR, which had the effect of increasing the SEs. The subject of SFOAEs measured in human ears at f_p in the presence of a second tone of much higher frequency has been a subject of recent interest (Shera *et al.*, 2004; Siegel *et al.*, 2004). The present study limited the maximum f_s/f_p , as well as the maximum stimulus levels, to ranges in which the two-tone suppression mechanism was expected, and subsequently confirmed, to be the dominant source mechanism for SFOAEs.

G. Implications

OAEs are useful clinically for detecting ears at risk for sensorineural hearing loss. The present results in normal-hearing adults suggest the potential use of SFOAE suppression to evaluate cochlear compression and gain associated with normal OHC function. While the complete research protocol took 10 h per subject, it is possible that cochlear compression and gain might be assessed using a significantly shorter protocol with only two suppressor frequencies, one slightly larger than f_p and another an octave below, combined with a restricted range of suppressor levels. A relatively short test to measure cochlear compression and cochlear gain associated with normal OHC functioning might have clinical benefits. An analogous test based on DPOAE suppression already exists, but interpretable results in normal-hearing and hearing-impaired subjects were obtained only for an f_2 of 4 kHz (Gorga *et al.*, 2003). The current study obtained results on SFOAE suppression at probe frequencies of 1, 2 and 4 kHz, with results in some ears obtained at 0.5 and 8 kHz. More research is needed to assess SFOAE suppression in subjects with OHC dysfunction.

V. CONCLUSIONS

SFOAEs provide a noninvasive measure of cochlear mechanics in adult human ears. Two-tone suppression of SFOAEs is similar to suppression effects reported in basilar-membrane measurements, neural recordings, and simultaneous behavioral masking in terms of the level and frequency dependence of STCs. The SFOAE STC was parametrized in terms of rate of growth of suppression, Q_{ERB} , the compressive slope of off-frequency growth-of-suppression responses, and tip-to-tail difference, which serves as a conservative measure of cochlear gain. The SFOAE parameter values were generally similar to the corresponding parameters in physiological studies of nonhuman mammalian cochlea and in psychoacoustical studies of normal-hearing humans.

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APPENDIX

SFOAE MEASUREMENT PROCEDURES

This Appendix describes details of the SFOAE measurements. Each stimulus frequency was constrained to have an integral number of periods within the elementary buffer length of $N=512$ samples, so that the nominal frequencies differed from actual test frequencies. For example, the nominal f_p of 0.5 kHz was a tone generated with a frequency of 0.517 kHz.

DAC1 and DAC2 denote channels 1 and 2, respectively, of the DACs on the sound card, with each channel driving one probe receiver. Different data acquisition procedures were used for f_p at 0.5 and 1 kHz than for f_p at 2, 4 and 8 kHz because of the longer SFOAE latencies at lower f_p . A stimulus block was constructed of N_s elementary buffers with the f_p stimulus presented through DAC1 (with zeros presented through DAC2), N_s buffers with f_s presented through

DAC2 (with zeros presented through DAC1), and N_s buffers with f_p presented through DAC1 and f_s presented through DAC2. The stimulus block thus contained $3N_s$ elementary buffers, meaning that the signal recorded through the ADC comprised three N_s buffers.

An acoustic discontinuity was created each time the stimulus changed (from f_p alone, to f_s alone, to their joint presentation, and so forth). In addition, a system delay of the ADC relative to the DACs, which included effects of digital filters in the converters, meant that the initial response buffer for f_s contained some of the response from f_p , and, similarly, for the other discontinuities.

These artifacts were eliminated by discarding the first M_s elementary buffers of each block of N_s elementary buffers ($M_s < N_s$). The number of saved responses associated with each stimulus block was $N_s - M_s$ for each response type (f_p alone, f_s alone, f_p and f_s jointly presented). For low probe frequencies, the sizes $N_s=7$ and $M_s=2$ were chosen, so that five buffers were saved for each response type. This resulted in an effective waiting time of $M_s=2$ elementary buffers, or 46 ms, between saved buffers. The transient OAE response associated with any acoustic discontinuity would have sufficient time to decay with respect to the continuous, synchronous-evoked response that was the signal of interest. For high probe frequencies, the sizes $N_s=5$ and $M_s=1$ were chosen, so that the number of saved buffers for each response type was $N_s - M_s=4$ buffers. The 23 ms waiting time associated with discarding one elementary buffer was sufficiently long with respect to system delays and OAE latencies at these higher frequencies to ensure that the response in the last four buffers was stationary (system delays were shorter than OAE latencies). Pilot data analyzed in Schairer *et al.* (2003) and additional new pilot data confirmed that these choices of numbers of discarded buffers gave substantively identical results when compared to tests with larger numbers of discarded buffers.

One advantage of interpolating between the different stimulus types during data collection is that the effects of slowly varying noise signals in the environment tended to cancel out, e.g., any effect of slowly varying static pressure within the middle-ear cavities.

Data collection continued until R sets of responses were acquired, with $R=15$ for low probe frequencies and $R=16$ for high probe frequencies. The time to collect data at particular stimulus condition (i.e., for fixed f_p, L_p, f_s, L_s) was $R * N_s * 3 * N_{22050}$, or 7.3 s at low probe frequencies and 5.6 s at high probe frequencies. The number of independent buffers saved for each stimulus type was $R * (N_s - M_s)$, or 75 buffers for low probe frequencies and 60 buffers for high probe frequencies.

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FIG. 1.

For subject 1 at $f_p=1$ kHz, SFOAE residual SPL (solid lines) and noise SPL (dashed lines) are plotted vs L_s at suppressor frequencies $f_s < f_p$ in the left column, and $f_s > f_p$ in the right column. Lines are thicker for f_s closer to f_p . L_p increases from top to bottom row. The set of possible values of $f_s < f_p$ are specified in Sec. II, but data are plotted only when the SNR criterion was satisfied. A saturation region (horizontal solid line) shows when SFOAE is fully suppressed. Note that this value is independent of f_s and provides the SPL of the total SFOAE. STCs are constructed at a criterion SPL that is 10.7 dB below the saturation level (shown by horizontal dotted line).

FIG. 2. SFOAE residual plots for subject 15 at $f_p=0.5$ kHz. Plotting conventions are the same as those in Fig. 1.

FIG. 3.

SFOAE suppression results for subject 5 at $f_p=4$ kHz, shown as SFOAE SPL vs. f_s/f_p (left column) and the same data shown as SFOAE Suppression Sensitivity Level vs. f_s/f_p (right column). L_p increases from 20 to 60 dB SPL in 10 dB steps from top to bottom row. Thicker contour lines show higher L_s decreasing in 6 dB steps from 80 down to 14 dB SPL.

FIG. 4.

SFOAE suppression results for subject 5 at $f_p=4$ kHz. Phase change vs. f_s/f_p . L_p increases from 20 to 60 dB SPL in 10 dB steps from top to bottom row. Thicker contour lines show higher L_s decreasing in 6 dB steps from 80 to 14 dB SPL.

FIG. 5.

Original and repeated tests (panels A and B, respectively) of STCs in subject 23 measured 30 days apart. SFOAE STCs are plotted at each octave of f_p from 0.5 to 8.0 kHz. Line thickness increases with increasing L_p , with adjacent L_p 's coded with alternating solid and dashed lines (thickest solid line is $L_p=60$ dB SPL, thinnest is 20 dB SPL).

FIG. 6.

Mean group SFOAE STC at each f_p from 0.5 to 8.0 kHz averaged across subjects based on the decrement criterion of 10.7 dB. Line thickness increases with increasing L_p , with adjacent L_p 's coded with alternating solid and dashed lines. Every other STC shows ± 1 SE as error bars.

FIG. 7.

Mean group SFOAE STC phase based on the decrement criterion of 10.7 dB. Similar plot conventions as those in Fig. 6

FIG. 8.

Mean of the rate of growth of SFOAE suppression vs. f_s/f_p , at f_p from 0.5 to 8.0 kHz in different panels, and at L_p from 20 to 60 dB SPL (thicker lines for higher levels) within each panel. Every other slope curve shows ± 1 SE as error bars.

FIG. 9.

The mean and ± 1 SE of Q_{ERB} of the STC is plotted as a function of f_p for L_p 's ranging from 20 to 60 dB SPL (thicker lines for larger L_p). The short dotted black line is the behavioral Q_{ERB} based on simultaneous masking using notched noise (Glasberg and Moore, 1990). The dashed-dotted black line is a measure of the behavioral Q_{ERB} based on nonsimultaneous masking and is a curve derived from SFOAE latency data assuming that SFOAEs are generated by a minimum-phase system (Shera *et al.*, 2002).

FIG. 10.

Plots of threshold L_s (dB SPL) vs. L_p , with each panel showing results for f_p at octaves from 0.5 to 8 kHz. Dashed gray lines show individual-subject data for on-frequency suppressors, i.e., suppressor frequencies just above the probe frequencies ($f_s/f_p \approx 1.03$). Solid gray lines show individual-subject data for off-frequency suppressors, i.e., for f_s an octave below f_p . The group mean ± 1 SE are plotted using black lines for all stimulus conditions with data from at least two subjects.

FIG. 11.
Slopes for GOS on-frequency and off-frequency responses and equivalent BM compression.

FIG. 12.

Mean ± 1 SE of the tip-to-tail difference of the SFOAE STC vs. probe frequency. Each curve represents different L_p . Tip-to-tail difference functions are slightly displaced along the horizontal axis to improve clarity. The variation of the tip-to-tail difference with L_p is implicitly represented at each f_p by the tip-to-tail differences along each vertical slice through the individual curves.

FIG. 13.
Model of a compressive and saturating nonlinear growth response in the cochlea.