Temporal aspects of suppression in distortion-product otoacoustic emissions^{a)}

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This study examined the time course of cochlear suppression using a tone-burst suppressor to measure decrement of distortion-product otoacoustic emissions (DPOAEs). Seven normal-hearing subjects with ages ranging from 19 to 28 yr participated in the study. Each subject had audiometric thresholds ≤ 15 dB HL [re ANSI (2004) *Specifications for Audiometers*] for standard octave and inter-octave frequencies from 0.25 to 8 kHz. DPOAEs were elicited by primary tones with $f_2 = 4.0$ kHz and $f_1 = 3.333$ kHz ($f_2/f_1 = 1.2$). For the f_2 , L_2 combination, suppression was measured for three suppressor frequencies: One suppressor below f_2 (3.834 kHz) and two above f_2 (4.166 and 4.282 kHz) at three levels (55, 60, and 65 dB SPL). DPOAE decrement as a function of L_3 for the tone-burst suppressor was similar to decrements obtained with longer duration suppressors. Onset- and setoff-latencies were ≤ 4 ms, in agreement with previous physiological findings in auditory-nerve fiber studies that suggest suppression results from a nearly instantaneous compression of the waveform. Persistence of suppression was absent for the below-frequency suppressor ($f_3 = 3.834$ kHz) and was ≤ 3 ms for the two above-frequency suppressors ($f_3 = 4.166$ and 4.282 kHz).

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I. INTRODUCTION

In the context of the auditory system, suppression is the reduction in the response of one sound by the simultaneous presentation of another sound. Distortion-product otoacoustic emissions (DPOAEs) are sounds emitted from the cochlea in response to a two-tone stimulus as byproducts of the cochlea's nonlinear mechanics. In addition to measuring the decrease in DPOAE level as a function of suppressor level, this study measured suppression onset (initiation of suppression) and setoff¹ (termination of suppression) latencies for tone-burst suppressors in normal-hearing subjects. The experimental paradigm also enabled the measurement of persistence, i.e., the continuation of suppressive effects after suppressor termination.

Suppression was first described by Wever *et al.* (1940) based on measurements of the cochlear microphonic. Since then, suppressive effects have been investigated at all levels of the auditory periphery: In physiological studies of auditory-nerve fibers (ANFs) (e.g., Galambos and Davis, 1944; Nomoto *et al.*, 1964; Sachs and Kiang, 1968; Sachs, 1969; Arthur *et al.*, 1971; Abbas and Sachs, 1976; Javel *et al.*, 1978, 1983; Costalupes *et al.*, 1987; Delgutte, 1990; Temchin *et al.*, 1997), in the responses of outer hair cells (OHC) and inner hair cells (IHC) (e.g., Sellick and Russell, 1979; Cheatham and Dallos, 1989; Nuttall and Dolan, 1993), and

in basilar membrane (BM) mechanics (e.g., Ruggero *et al.*, 1992; Nuttall and Dolan, 1993; Rhode and Cooper, 1993; Cooper, 1996; Cooper and Rhode, 1996; Robles *et al.*, 1997).

Cochlear suppression latencies can be measured by means of DPOAEs; furthermore, DPOAE iso-suppression tuning curves mirror the ear's frequency selectivity (Kummer *et al.*, 1995; Abdala *et al.*, 1996; Gorga *et al.*, 2003). Suppression-growth functions of DPOAEs share many similarities with physiological measures of cochlear response, and have been studied in normal and hearing-impaired ears (e.g., Abdala, 1998; Martin *et al.*, 1998; Abdala and Fitzgerald, 2003; Gorga *et al.*, 2008, 2011). DPOAEs originate in response to a two-tone stimulus as byproducts of the cochlea's nonlinear mechanics. The lower-primary frequency of the two-tone stimulus is referred to as f_1 and its level as L_1 ; the higher frequency is denoted as f_2 and its level as L_2 . Intermodulation distortion products originate from the cochlea as tones at frequencies that are linear combinations of the primary frequencies. The response is typically measured at the $2f_1 - f_2$ frequency (f_d), because it is the largest distortion product in humans. It is generally assumed that DPOAEs arise from two sources: The f_2 place and the DPOAE-frequency place (f_d) (Zweig and Shera, 1995; Talmadge *et al.*, 1998; Shera and Guinan, 1999). The first source (wave-fixed or distortion) is thought to arise from the nonlinear interaction between the f_1 and f_2 primary tones; the interaction creates energy (i.e., distortion products) at the f_2 place that travels both apically and basally within the cochlea. The second source (place-fixed) is the f_d place on the BM where some of the apically traveling energy is reflected back basally by irregularities in the cochlea to

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produce a second DPOAE component from the f_d place. These two DPOAE components combine to produce the emission signal measured in the ear canal. By keeping the level of the two-tone stimulus constant and varying f_3 in frequency and level, growth of DPOAE suppression can be measured. Growth of DPOAE suppression follows the same pattern as observed in physiological studies, in that DPOAE suppression grows more rapidly for suppressor frequencies lower than f_2 , compared to suppressors close to or slightly above f_2 (e.g., Brown and Kemp, 1984; Harris *et al.*, 1992; Kummer *et al.*, 1995; Abdala, 1998; Abdala and Chatterjee, 2003; Gorga *et al.*, 2003). As stated earlier, these general trends are at least qualitatively similar to trends observed in both ANF and BM responses and support the use of DPOAEs to explore temporal aspects of suppression.

Attempts to model suppression have found it difficult to simulate the frequency and level dependence asymmetry (e.g., Engebretson and Eldredge, 1968; Pfeiffer, 1970; Kim *et al.*, 1973; Duifhuis, 1975; among others). The most successful models to date include a compressive nonlinearity of the BM, suggesting that the role of the OHCs is to compress the operating range of the cochlea into an optimum range for the IHCs (e.g., Neely and Kim, 1982; Zwicker, 1985; Yates *et al.*, 1989; Geisler *et al.*, 1990; among others). This compressive nonlinearity in turn generates both suppression and two-tone interference (Goldstein and Kiang, 1968; Nuttall *et al.*, 1990; Robles *et al.*, 1991). Attempts to model suppression should consider also its time course. Any evidence of persistence in suppression beyond the duration of the suppressor would have implications for modeling of cochlear mechanics, determining the masking effects of background noise, as well as in the peripheral encoding of speech stimuli for the development of signal processing in hearing aids.

The main purpose of this study was to measure latencies of mechanical suppression, using a novel method to measure temporal suppression (TS) in DPOAEs that parallels previous physiological measures.

II. METHODS

A. Subjects

Seven normal-hearing subjects with ages ranging from 19 to 28 yr participated in this study. Each subject had audiometric thresholds ≤ 15 dB HL (re ANSI, 2004) for standard octave and inter-octave frequencies from 0.25 to 8 kHz. Subjects were recruited from a database of potential research subjects that is maintained at Boys Town National Research Hospital in Nebraska; they were paid for their participation. Additional criteria included measurable DPOAEs during a screening procedure and a normal 226-Hz tympanogram on each day on which DPOAE measurements were made. Only one ear (the better ear) of each subject was selected for study.

B. Stimuli and apparatus

DPOAEs were elicited by primary tones with $f_2 = 4.0$ kHz and $f_1 = 3.333$ kHz ($f_2/f_1 = 1.2$). The suppressor (f_3) frequencies included one suppressor below f_2 (3.834 kHz) and

two above f_2 (4.166 and 4.282 kHz). The stimulus consisted of 2000 consecutive intervals each 128 ms in duration. The probe (f_1 and f_2) was continuous across the entire 256 s stimulus interval. The suppressor was presented as Blackman-windowed tone bursts of 40 ms duration, which were offset 8 ms from the beginning of each 128 ms stimulus interval to parallel physiological measures of two-tone suppression. DPOAE stimuli were produced at a sampling rate of 32 000 Hz by a 24-bit soundcard (Layla 3G, Echo Digital Audio Corp., Santa Barbara, CA) that drove a custom-built sound source and received input from a probe-microphone system (ER-10B+, Etymotic Research, Elk Grove Village, IL). For all DPOAE measurements, a frequency-domain heterodyne technique (e.g., Kim *et al.*, 2001; Neely *et al.*, 2005) was used for tracking the time course of both stimulus and response levels from the recorded waveforms. An initial fast Fourier transform (FFT) was performed of the complete pressure waveform, representing 256 s with a sample rate of 32 kHz. A band of (positive) frequencies surrounding the DPOAE frequency of interest (f_2) was selected and shifted and these frequency components were shifted down such that f_2 was positioned at the zero frequency. A Blackman-shaped low-pass filter extending ± 120 Hz around the zero frequency was applied to the shifted spectrum and then an inverse FFT was performed. The resultant signal represents the magnitude and phase of the DPOAE component as a function of time. This magnitude-versus-time function corresponds to the temporal "envelope" of the DPOAE component (i.e., Hilbert envelope). As a result of using this technique the sample size of stimulus and response buffers was 4096. Both output channels of the sound card were used during DPOAE measurements, with f_2 and f_3 presented on one channel and f_1 presented on the other one. For each f_3 , three TS functions were collected for three different suppressor levels.

C. Procedure

DPOAE data were collected with locally developed software (SYSRES, Neely and Stevenson, 2002). For f_2 , a TS function was obtained by presenting ipsilaterally a third (suppressor) tone (f_3) at one of the three suppressor frequencies ($f_3 = 3.834, 4.166$, and 4.282 kHz), whose level (L_3) was set to each of three levels (55–65 dB SPL, 5-dB steps). The level of the higher-primary frequency (L_2) was set to 50 dB SPL while the level of f_1 (L_1) was set to 65 dB SPL. The f_1 level is in agreement with the optimal L_1 average determined for 4 kHz in unpublished findings from our laboratory for a group of normal-hearing subjects ($N = 103$). Data collection began at the lowest L_3 and proceeded to the highest L_3 for each suppressor. A reliability check was performed at the end of each session by retesting $f_3 = 4.166$ kHz at 65 dB SPL. Thus, ten suppression functions were collected per subject at each of three sessions for a total of 30 functions at the completion of the study. Each session lasted for 60–90 min. In the ear forward-pressure level (FPL) calibration (Scheperle *et al.*, 2008) was used to determine stimulus levels. FPL calibration avoids the influence of standing waves and

results in less variability in DPOAE measurements (Scheperle *et al.*, 2008).

III. RESULTS

All temporal aspects of the results were quantified via MATLAB; however to provide the reader with a visual representation of the test paradigm and calculations, the data are presented in visual form as described below. Temporal features of the data are shown in Fig. 1 as follows: The uppermost horizontal line represents the level of f_1 (L_1) at 65 dB SPL, the second horizontal line from the top is the level of f_2 (L_2) at 50 dB SPL, and the upward rounded line represents the level (L_3) of the suppressor (i.e., f_3 at 55 dB SPL). The third horizontal line represents DPOAE level; the downward deviation indicates the time course of the suppression in the presence of the suppressor. The dashed line labeled $L_d - 3$ dB is 3 dB below the unsuppressed DPOAE level and represents 3 dB of suppression. The cross and asterisk superimposed on L_3 are suppressor onset and setoff, respectively, in milliseconds; the cross and asterisk on $L_d - 3$ dB are decrement onset and decrement setoff, respectively, in milliseconds. The time difference between suppressor onset and decrement onset was labeled suppression-onset delay. Onset-latency delay was defined as the first DPOAE level point exhibiting ≥ 3 dB of suppression. The time difference between suppressor setoff and decrement setoff was labeled suppression-setoff delay.

Decrement setoff was defined as the last point exhibiting ≥ 3 dB of suppression. Finally, the difference between suppression-setoff delay and suppression-onset delay was taken as a measure of persistence of the response. Persistence was defined as the duration in milliseconds that the response was

FIG. 1. (Color online) Example of TS function for $f_3 = 3.834$ kHz as a function of duration in milliseconds. The uppermost horizontal line represents L_1 at 65 dB SPL, the second horizontal line from the top is L_2 at 50 dB SPL, and the upward rounded line represents L_3 at 55 dB SPL. The third horizontal line with the downward hump represents the measured decrement function. The dashed line, $L_d - 3$ dB, represents 3 dB of suppression. The cross and asterisk superimposed on L_3 are suppressor onset and setoff, respectively, in milliseconds; the cross and asterisk on $L_d - 3$ dB are decrement onset and decrement setoff, respectively, in milliseconds.

observed following the suppressor setoff. As can be seen in the example in Fig. 1, suppression-onset delay for $f_3 = 3.834$ kHz at 55 dB SPL is 3 ms (i.e., 27–24 ms), suppression-setoff delay is 1 ms (i.e., 41–40 ms). Persistence calculated as setoff delay minus onset delay (i.e., 1 – 3 ms = –2 ms) is a negative value, suggesting there is no persistence for the variables depicted because the response is over before the suppressor ends.

Figure 2 shows the time course of DPOAE level for subject 6 for each suppressor frequency and each suppressor level. Each column represents a different f_3 increasing from left to right (3.834–4.282 kHz) and each row represents a different L_3 increasing from top to bottom (55–65 dB SPL). Atop each DPOAE level curve, two horizontal lines depict the onset and setoff of both the suppressor (thick line) and the suppression (thin line). The difference between the lengths of these two lines represents *persistence* of the suppression. In this example, persistence values are negligible.

To quantify suppression in decibels, the changes in DPOAE level due to the suppressor were converted to decrement (L_d) (i.e., amount of suppression in decibels) as previously described (Gorga *et al.*, 2002). That is, the decrement vs L_3 functions for each f_3 were transformed by the following equation:

$$D = 10 \log(10^{\text{decr}/10} - 1) \quad (1)$$

and fit by a linear regression of D onto L_3 . Lines were fit only to the range, $-5 < D < 20$. Each of these linear equations was then solved for the L_3 that resulted in a 3-dB decrement. As such, $D = 0$ when $\text{decr} = 3$ dB. The same linear regressions were used to provide slope estimates for the decrement functions. Figure 3 shows representative decrement functions as a function of L_3 for all subjects at 4.166 kHz ($L_3 = 60$ dB SPL). Only decrement values with signal-to-noise (SNR) 3 dB were included for this calculation. Both real and fitted data are included in the figure. The estimated decrement slopes had a mean value of 1.0 dB/dB (SD = 0.2 dB). Analysis of variance did not reveal statistically significant frequency and level effects. This mean value is consistent with previously reported decrement slopes when f_3 is nearly equal to f_2 (e.g., Gorga *et al.*, 2003).

Figure 4 shows the mean suppression-onset delay values in milliseconds and the standard deviations for all subjects as a function of L_3 with f_3 as the parameter. The mean onset-latency value was ≤ 4.2 ms with a standard deviation of 1.0 ms. The mean onset latencies for suppression did not show a significant level or frequency effect. For $f_3 = 3.834$ at 55 dB SPL, suppression onset appears to be additionally delayed due to never achieving full-on suppression. At 60 and 65 dB SPL, the onset latencies of the three suppressors converge with a mean of ≤ 3 ms and a standard deviation of 0.3 ms.

The mean suppression-setoff delays are shown in Fig. 5 for all subjects as a function of L_3 with f_3 as the parameter. As previously mentioned, this was the difference in latency between suppressor setoff and suppression setoff. The main finding, similar to the onset-latency values, was that suppression-setoff delays were always lower (≤ 2 ms, SD = 0.8) for the low-side suppressor and converged for the high-side

FIG. 2. (Color online) DPOAE level as a function of time for subject 6. Each row represents a different L_3 increasing from top to bottom (55, 60, and 65 dB SPL). Each column represents a different f_3 increasing from left to right (3.834, 4.166, and 4.282 kHz). The thick top line segment in each panel represents the duration of the suppressor and the thin line segment, the duration of the decrement response.

suppressors (≤ 3 ms, $SD = 0.8$). Analysis of variance did not reveal statistically significant differences for frequency or level effects.

Figure 6 presents the individual values for persistence in milliseconds for all subjects; analysis of variance did not reveal statistically significant differences for frequency and level effects. For the low-side suppressor (f_3) there is no evidence of persistence whereas the data for the high-side suppressors ($f_3 = 4.166$ and 4.282 kHz) reveal values that are ≤ 3 ms with a standard deviation of 1.3 ms.

IV. DISCUSSION

The purpose of this study was to examine the time course of mechanical suppression using a novel method to measure suppression of distortion-product otoacoustic emissions (DPOAEs) in which the suppressor was presented as tone bursts to best parallel physiological paradigms of two-

tone suppression. The role of OHCs in the production of suppression appears firmly established as indicated by the absence of the phenomenon in studies of cochlear regions that have been partially or completely devoid of OHCs by chemical or traumatic manipulation (e.g., [Ruggero and Rich, 1991](#); [Robles and Ruggero, 2001](#)). The amount of suppression that is observed depends on many factors, including both the frequency and intensity of the suppressor tones (e.g., [Robles et al., 1991](#); [Nuttall and Dolan, 1993](#); [Rhode and Cooper, 1993](#); [Cooper, 1996](#); [Geisler and Nuttall, 1997](#); [Rhode and Recio, 2001](#)). Suppression has been shown to be asymmetrical for suppressor tones above and below characteristic frequency (CF), the frequency to which the ANF or the location of the BM measurement is most sensitive to (e.g., [Prijs, 1989](#); [Delgutte, 1990](#)), both in terms of the shape of the suppression threshold tuning curve and in the suppression growth rate. Suppressor tones an octave or more below CF have higher suppression thresholds, compared to suppressor

FIG. 3. Decrement as a function of L_3 (60 dB SPL) with f_3 (4.166 kHz) as the parameter. Both real and fitted data are represented. Each panel shows the results for a different subject; the panel in the lower right shows means across subjects.

FIG. 4. Mean suppression-onset delay latencies in milliseconds across repetitions for all subjects as a function of L_3 with f_3 as the parameter. Suppressors are represented as follows: $\square$ = 3.834 kHz, $\circ$ = 4.166 kHz, and $\triangle$ = 4.282 kHz. Each panel shows the results for a different subject; the panel in the lower right shows means across subjects.

FIG. 5. Mean suppression-setoff delay latencies in milliseconds across repetitions for all subjects as a function of L_3 with f_3 as the parameter. Suppressors are represented as follows: $\square$ = 3.834 kHz, $\circ$ = 4.166 kHz, and $\triangle$ = 4.282 kHz. Each panel shows the results for a different subject; the panel in the lower right shows means across subjects.

FIG. 6. Mean persistence latencies in milliseconds across repetitions for all subjects as a function of L_3 with f_3 as the parameter. Each panel shows the results for a different subject; the panel in the lower right shows means across subjects.

tones close to CF; however, once suppression threshold is exceeded suppression grows faster for suppressors lower in frequency than CF. Suppressors higher in frequency relative to CF have lower suppression thresholds and the suppressive effect grows slowly as suppressor level is increased. Suppression has been explained as a process tied to the saturating input–output functions of the OHCs for frequencies whose traveling waves overlap (Geisler *et al.*, 1990).

Studies have looked at rate suppression (Arthur *et al.*, 1971) where the overall response is reduced by the presentation of a second tone, and synchrony suppression (e.g., Javel *et al.*, 1983; Ruggero *et al.*, 1992; Geisler and Nuttall, 1997) where the response component to a sound is modulated by the presentation of a second lower-frequency sound. The latency of suppression has received limited attention in the literature partly due to technical limitations. An intrinsic difficulty in any measure of suppression is the need to extricate the effects of dispersion of the traveling wave from the effects of any inherent onset- or setoff-latencies of suppression. Arthur *et al.* (1971) measured the onset latency of excitation and suppression to gated tones in primary auditory neurons of cats; however, the use of gated tones (i.e., rise/fall times of 2.5 ms) to prevent generation of transient responses obscured some of their suppression onset/setoff latency measures. In spite of the reported technical issues, they measured suppression latencies of ≤ 2 ms depending upon the frequency of the suppressor with respect to the CF. The onset latency difference between excitation and suppression was 0.1 ms.

Differences between the paradigms of ANF and DPOAE measurements (i.e., travel time) notwithstanding, it is noteworthy that the values observed here are comparable to the ones reported for ANF measurements by Arthur *et al.* (1971), and in contrast to van der Heijden and Joris (2005) who found longer time constants. Mean suppression-onset (3–4.2 ms) and decrement-setoff latencies (2–3 ms) were observed. Values for the below-frequency and above-frequency suppressors showed an asymmetry with the largest values (4.2 ms) observed for the below-frequency suppressors at the lowest L_3 ; however, frequency and level effects were not statistically significant. Suppression thresholds for low-side suppressors have been reported to lie between 55 and 65 dB SPL (Sen and Allen, 1999), so this finding is not unexpected.

To circumvent the issues associated with transients evoked by very short rise/decay times in tonal stimuli; van der Heijden and Joris (2005) used multitone complexes. These complexes contained a set of primary frequencies with spacing designed to produce a number of beat frequencies arising from the interaction between the primaries that were used to measure the delay of suppression in the ANFs of cats. Once the relative phases of the primaries were extracted from the phases of the beats and travel time along the cochlea was taken into account, they reported that low-side suppression originates from a gain-control mechanism with an integration time in the order of two cycles of CF. According to the authors, their findings run counter to the notion that a memory-less saturating nonlinearity can explain two-tone suppression by itself. They proposed,

instead, some type of automatic gain control (AGC) rather than an instantaneous compression of the waveform. The implication of their study is that there is a persistence of the suppressive response. Contrary to the latter findings, the very short time constants of suppression reported by previous authors (Kiang *et al.*, 1965; Arthur *et al.*, 1971, 1976) suggest that suppression is not the result of inhibitory synapses in the cochlea because there is no time for synaptic delay (~ 1 ms). There is also experimental evidence (Kiang *et al.*, 1965) that suppression is not the result of the activity of the olivocochlear bundle. Our findings indicate that the below-frequency suppressor did not exhibit persistence of the response. For the above-frequency suppressors, mean persistence values were below 3 ms.

Delgutte (1990) has suggested that suppression is a major component of psychophysical masking and that many aspects of masking can be understood from suppression. Results of a recent comparison between psychophysical masking and DPOAE suppression in the same subjects were consistent with the view that suppression accounts for most of the difference between simultaneous masking and forward masking (Rodriguez *et al.*, 2010).

Psychoacoustic temporal resolution functions measure the auditory system's ability to follow the time-varying level fluctuations of a signal. Early studies of temporal resolution (e.g., Plomp, 1964; Smiarowski and Carhart, 1975; Penner, 1978; Zwicker, 1984) suggest a very fast initial time constant for excitation. Plomp's findings suggest two stages of residual excitation: A short one over in under 3 ms and a longer one that decays linearly over log time up to about 200–300 ms. Similar findings were described by subsequent studies (Smiarowski and Carhart, 1975; Penner, 1978; Zwicker, 1984): 2–4 ms, for the shortest masker durations with an asymptote of about 200 ms for the longest masker durations. However, ANF studies (Arthur *et al.*, 1971; Kiang *et al.*, 1965) would suggest that, peripherally, excitation and suppression are over in less than 1 ms.

The auditory system's ability to detect a temporal gap as short as 3 ms, as well as integrate power over time constants as long as 200–300 ms, has been called the temporal resolution–temporal integration paradox (Viemeister and Plack, 1993). Models have been proposed to account for the temporal resolution–temporal integration paradox (e.g., Penner 1975, 1978; Zwicker, 1984; Moore *et al.*, 1988; Viemeister and Wakefield, 1991; Oxenham and Plack, 2000; Oxenham, 2001). One of the more recent models, the temporal-window model (e.g., Moore *et al.*, 1988; Oxenham and Plack, 2000; Oxenham, 2001) seems to have had the most influence in recent years. Persistence of neural excitation plays an essential role in the temporal-window model of forward masking. Forward masking in the temporal-window model results because the masker response is assumed to last beyond the stimulus offset in the form of persistent excitation, and the extended masker-induced firing swamps responses to the subsequent probe tone. Alternatively, it has also been explained as an internal representation of the signal that persists after masker termination, possibly due to central perceptual mechanisms (Penner, 1975). We looked for evidence of a *physical* correlate of persistence in our DPOAE suppression

measurement by examining differences between onset- and setoff-latencies. The observed persistence values on the order of 3–4 ms are smaller than required for the temporal-window model (≤ 20 ms). Our results seem to favor the alternative view that forward masking is more likely due to adaptation. We agree with the conclusion offered by Moore *et al.* (1988) and Oxenham (2001) that forward masking is influenced by some process, such as adaptation, which is not as adequately represented by the temporal-window model.

Lastly, it is noteworthy that the decrement functions obtained with tone-burst suppressors are similar to those obtained with tonal stimuli (Gorga *et al.*, 2011). Gorga *et al.* (2011) measured suppression tuning curves at eight f_2 frequencies ranging from 0.5 to 8 kHz for L_2 levels ranging from 10 to 60 dB SPL. For each f_2 , L_2 combination, suppression was measured for 9 or 11 suppressor frequencies (f_3) whose levels varied from –20 to 85 dB SPL. The authors reported decrement slopes that were about 1 dB/dB for $f_3 \approx f_2$ for the 55–65 dB SPL range for $f_2 = 4$ kHz. Our findings for the decrement function slope for the three f_3 are the same which is not surprising since we did not use suppressors that were further away than 0.282 kHz from $f_2 = 4$ kHz.

In summary, there does not appear to be a significant difference between decrement functions obtained with tonal stimuli and those measured with tone bursts in this study. The values observed in this study for suppression-onset, decrement-setoff latency, and persistence fall within a time-window similar to that observed in ANF studies (Arthur *et al.*, 1971). Of note is the fact that the persistence values are consistent with temporal resolution studies (Plomp, 1964; Smiarowski and Carhart, 1975; Penner, 1978; Zwicker, 1984). In view of the non-invasive nature of this paradigm, as compared to ANF studies, future efforts will be devoted to include additional parameters to determine potential clinical applications. For example, knowledge of temporal suppressive effects in different clinical populations might have diagnostic value as well as implications for hearing aid fittings.

V. CONCLUSIONS

This study measured temporal features of DPOAE suppression. The findings suggest that, similar to previous ANF studies, suppression onset- and setoff-latencies are on the order of 3–4 ms. Persistence of suppression was absent for the below-frequency suppressor ($f_3 = 3.834$ kHz) and ≤ 3 ms for the two above-frequency suppressors ($f_3 = 4.166$ and 4.282 kHz). Tone-burst suppression produced decrement slope functions similar to those obtained with tonal stimuli. For the parameters included here, an almost instantaneous nonlinearity seems to underlie suppressive effects. The findings suggest that models of forward masking based on adaptation rather than persistence might better represent the observed effects of suppression.

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¹The term setoff is introduced in this paper as an alternative to offset to avoid confusion with the more common meaning of offset as a vertical displacement.

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