Pressurized transient otoacoustic emissions measured using click and chirp stimuli

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Transient-evoked otoacoustic emission (TEOAE) responses were measured in normal-hearing adult ears over frequencies from 0.7 to 8 kHz, and analyzed with reflectance/admittance data to measure absorbed sound power and the tympanometric peak pressure (TPP). The mean TPP was close to ambient. TEOAEs were measured in the ear canal at ambient pressure, TPP, and fixed air pressures from 150 to −200 daPa. Both click and chirp stimuli were used to elicit TEOAEs, in which the incident sound pressure level was constant across frequency. TEOAE levels were similar at ambient and TPP, and for frequencies from 0.7 to 2.8 kHz decreased with increasing positive and negative pressures. At 4–8 kHz, TEOAE levels were larger at positive pressures. This asymmetry is possibly related to changes in mechanical transmission through the ossicular chain. The mean TEOAE group delay did not change with pressure, although small changes were observed in the mean instantaneous frequency and group spread. Chirp TEOAEs measured in an adult ear with Eustachian tube dysfunction and TPP of −165 daPa were more robust at TPP than at ambient. Overall, results demonstrate the feasibility and clinical potential of measuring TEOAEs at fixed pressures in the ear canal, which provide additional information relative to TEOAEs measured at ambient pressure. © 2018 Acoustical Society of America.

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NOMENCLATURE

ADC	analog-to-digital converter
CEOAE	click-evoked otoacoustic emission
DAC	digital-to-analog converter
ETD	Eustachian tube dysfunction
peSPL	peak-to-peak equivalent sound pressure level
SE	standard error of the mean
SEL	sound exposure level
SNR	signal-to-noise ratio
SFOAE	stimulus frequency otoacoustic emission
SPL	sound pressure level
TEOAE	transient-evoked otoacoustic emission
TPP	tympanometric peak pressure

I. INTRODUCTION

Transient-evoked otoacoustic emission (TEOAE) responses are an aural acoustic measurement of cochlear function associated with the compressive nonlinearity of outer hair cells. TEOAEs are measured by inserting a probe into the ear canal, presenting a transient sound from a sound source, and measuring the acoustical response of the ear canal, middle ear, and cochlea using a sensitive microphone within the probe (Kemp, 1978). The stimulus sound energy is forward transmitted through the ear canal and middle ear to the cochlea, within which the TEOAE is generated mainly through a process of coherent reflection (Zweig and Shera, 1995). The TEOAE is reverse transmitted through the middle ear to the ear canal. While TEOAEs are typically measured at ambient pressure in the ear canal, it may be clinically useful for some ears to measure the TEOAE at an air pressure different from ambient. This report¹ describes such pressurized TEOAEs measured in the ears of adults with normal hearing over a wider frequency range (up to 8 kHz) than previous

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measurements. It also describes a case study of pressurized TEOAE and reflectance measurements in an adult subject with Eustachian tube dysfunction (ETD) and an accompanying conductive hearing loss. This case study illustrates how pressurized TEOAEs might provide clinically relevant information beyond that in ambient TEOAE testing.

A. Previous research on pressurized TEOAEs

Early work showed that stimulus frequency otoacoustic emissions (SFOAEs) were sensitive to pressurization of the ear canal relative to ambient pressure (Kemp, 1979), and to hydrostatic pressure changes in the middle ear induced by body tilt (Wilson, 1980; Voss *et al.*, 2010). Such SFOAEs have a similar generation mechanism to TEOAEs (Shera and Guinan, 1999).

Pressurizing the ear canal over the tympanometric range reduced click-evoked otoacoustic emission (CEOAE) levels in adult ears relative to those measured at ambient pressure at frequencies below 2.6 kHz, with smaller differences at frequencies up to 5 kHz (Naeve *et al.*, 1992; Hauser *et al.*, 1993). CEOAEs recorded in young adult ears with a negative tympanometric peak pressure (TPP) had improved reproducibility when the ear canal was pressurized to the TPP (Trine *et al.*, 1993). Recordings at the TPP approximately equalized CEOAE spectral levels above 1.5–2 kHz (Marshall *et al.*, 1997) compared to ambient-pressure recordings. CEOAE amplitudes at the TPP were increased relative to amplitudes recorded at ambient pressure. Ear-canal pressure changes on the order of ± 200 daPa attenuated CEOAE levels the most below 2 kHz (Plinkert *et al.*, 1994). The largest level changes of CEOAEs in normal-hearing adult ears were observed at frequencies from 0.75 to 3 kHz with decreased CEOAE latency for positive and negative changes in air pressure relative to ambient (Konradsson *et al.*, 1999).

Changes in middle-ear pressure away from ambient conditions change both forward middle-ear transmission of the sound stimulus eliciting the TEOAE and reverse transmission of the TEOAE back to the ear canal (Naeve *et al.*, 1992; Konradsson *et al.*, 1999), with similar effects described for distortion-product otoacoustic emissions (OAEs) (Sun and Shaver, 2009; Sun, 2012). Based on recordings up to 4–5 kHz, the fact that TEOAE levels at the TPP are maximal at frequencies up to 2–3 kHz is why the recording of TEOAEs at an ear-canal pressure equal to that of the TPP is of clinical interest. Marshall *et al.* (1997) repeatedly tested one adult subject over 6 months who frequently had a range of negative TPPs out to -150 daPa, and found that TEOAEs recorded at the TPP were larger in level than TEOAEs at ambient pressure for frequencies up to 3.15 kHz, and smaller in level for higher frequencies up to 5 kHz. They recommended that TEOAEs be recorded at the TPP in long-term monitoring applications, in which the transmission characteristics of the middle ear may fluctuate between test dates.

The literature on pediatric measurements of TEOAEs at TPP is relevant because of the importance of TEOAE testing in newborn hearing screening programs, although no children were tested in the present study. Children ranging in age from 1 to 7 yrs have increased TEOAE pass rates in ears

tested at the TPP relative to ears tested at ambient pressure (Hof *et al.*, 2005). Their results showed that the signal-to-noise ratio (SNR) of TEOAEs between 1 and 4 kHz was improved when TEOAEs were recorded at TPP relative to ambient pressure. In a study of children between 0.5 and 9 yrs, the TEOAEs at TPP had increased a signal level relative to ambient pressure below 2 kHz, which a model explained as due to increased middle-ear compliance in the test at TPP (Hof *et al.*, 2012). TEOAEs recorded at both ambient pressure and TPP in children of age 3 to 39 months had a lower TEOAE level and SNR at ambient compared to at a TPP for frequencies between 1 and 4 kHz (Prieve *et al.*, 2008).

B. Pressurized TEOAEs represented using the analytic signal

This section summarizes how TEOAE responses were measured at ambient pressure in the ear canal using click and chirp stimuli (Keefe *et al.*, 2016), inasmuch as these procedures were also used to analyze pressurized TEOAEs in the present study. As further described below, each stimulus has an approximately constant incident sound pressure level (SPL) across frequency. Such a stimulus calibration produces generally similar TEOAEs up to 8 kHz in normal adult ears as TEOAEs elicited using stimuli calibrated with constant absorbed sound power across frequency (Keefe *et al.*, 2017). The key property of absorbed sound power is that its value measured at the probe tip is nearly equal to its value at the tympanic membrane, with only small amounts of sound power absorbed at the ear-canal walls. The present work describes methods for measuring pressurized TEOAEs up to 8 kHz and investigates whether pressurization affects TEOAEs differently according to their stimulus type.

The present work describes novel measurements of pressurization effects on TEOAE group delay (GD) and instantaneous frequency (IF), as well as on TEOAE group spread (GS) and instantaneous bandwidth (IB) (Keefe, 2012; Keefe *et al.*, 2016). These *signal-processing conditional moments* specify properties of TEOAEs in both time and frequency domains. These moments were only calculated at times and frequencies at which the TEOAE was classified as present. TEOAE amplitude was classified as present or absent based on the SNR, and the TEOAE phase was classified as synchronous or asynchronous using a coherence synchrony measure (CSM) (Keefe, 2012). CSM is based on the degree of synchrony of the TEOAE across the multiple buffers holding the TEOAE dataset. CSM varies from one in the case of perfect synchrony to zero for no synchrony. Each classification was based on a statistic with a p value of 0.05. A TEOAE was classified as present based on SNR if the measured SNR was greater than or equal to a critical SNR of $[10 \log_{10}(-2 \ln(2p))]$, or 6.6 dB. A TEOAE was classified as present based on CSM if the measured CSM was greater than or equal to the critical CSM. This was calculated in terms of p and the number of averaging blocks L by $\text{CSM}_{\text{crit}} = [(1 + 2L)^2 - (\ln p + (1 + 2L))^2]^{1/2} / (2L)$, with values of 0.351 for click TEOAEs and 0.429 for chirp TEOAEs. The SNR and CSM are not directly equivalent measures of the ability to extract a TEOAE signal from noise. SNR assesses the ability to extract the TEOAE level from

noise, while CSM assesses the ability to extract the TEOAE phase from noise.

The SNR and CSM of the TEOAE and its signal-processing moments are defined using a continuous-time, continuous-frequency representation of a TEOAE residual waveform $p_d(t)$, which is defined below, and its spectrum $P_d(f)$. The analytic signal $s(t)$ of $p_d(t)$ is defined with unit imaginary number j by (Cohen, 1995)

$$s(t) = p_d(t) + jp_{dH}(t), \quad (1)$$

in which $p_{dH}(t)$ is real and equal to the Hilbert transform of p_d . For $t > 0$, the complex analytic signal is expressed in terms of the real instantaneous amplitude $A(t)$ and phase $\Phi(t)$ by

$$s(t) = A(t) e^{j\Phi(t)}. \quad (2)$$

The spectrum $S(f)$ of the analytic signal is non-zero only for positive frequencies ($f > 0$) and expressed in terms of the TEOAE residual spectrum $P_d(f)$ by

$$S(f) = 2P_d(f). \quad (3)$$

It is parameterized in terms of real spectral amplitude $B(f)$ and phase $\Psi(f)$ by

$$S(f) = B(f) e^{j\Psi(f)}. \quad (4)$$

SNR is calculated from the coherent and incoherent averages across the L blocks using amplitudes $A(t)$ in the time domain and $B(f)$ in the frequency domain. CSM is calculated using the phasor $e^{j\Phi(t)}$ in the time domain and the phasor $e^{j\Psi(f)}$ in the frequency domain. CSM is defined as the average length of the phasors in the L blocks, and averaged within each half-octave bandwidth in the frequency domain and within each half-doubling in time in the time domain.

Using Eq. (2) for the analytic TEOAE waveform, IF and IB are (Keefe, 2012)

$$\begin{aligned} \text{IF}(t) &= \frac{1}{2\pi} \frac{d\Phi(t)}{dt}, \\ \text{IB}(t) &= \frac{1}{2\pi} \left| \frac{d\ln A(t)}{dt} \right|, \end{aligned} \quad (5)$$

in which IF and IB have units of frequency. IF was calculated in the present study at times for which CSM exceeded its critical value, and IB was calculated at times for which SNR exceeded its critical value. IF and IB were smoothed with an energy-weighted window over each half-doubling bin in time. The IF is the temporal phase gradient of the click TEOAE analytic waveform, or the equivalent click analytic waveform (described below) of the chirp TEOAE waveform. The IF provides a measure of the local frequency content of the TEOAE in time. The IB is a normalized temporal gradient of the SPL of the TEOAE, that is, its decay rate. Using Eq. (4) for the spectrum of the analytic TEOAE waveform, GD and GS are

$$\begin{aligned} \text{GD}(f) &= -\frac{1}{2\pi} \frac{d\Psi(f)}{df}, \\ \text{GS}(f) &= \frac{1}{2\pi} \left| \frac{d\ln B(f)}{df} \right|, \end{aligned} \quad (6)$$

with GD and GS having units of time. GD was calculated at frequencies for which CSM exceeded its critical value, and GS was calculated at frequencies for which SNR exceeded its critical value. GD and GS were smoothed with an energy-weighted window over each half-octave band. The GD is the spectral phase gradient of the complex spectrum of the analytic click TEOAE, or the equivalent click spectrum for the corresponding chirp TEOAE response. It provides a measure of the local temporal content of the TEOAE in frequency. The GS is a normalized spectral gradient of the SPL of the TEOAE, and is a measure of temporal dispersion across the spatial extent of the tonotopically-organized TEOAE reflection sites along the basilar membrane.

C. Goals

The measurement system used in the present study provided a means to combine TEOAE measurements with swept wideband tympanograms using the same probe, whereas previous research has either combined results from separate tympanometry and evoked OAE measurements, or measured evoked OAEs at a fixed pressure in the ear canal that was manually adjusted. In the present study, TEOAE responses were compared in a group of adult ears with normal hearing in recordings at ambient pressure in the ear canal, at fixed pressure over the tympanometric range, and at the TPP determined from swept tympanometry. This data set allowed analyses of how the TEOAE spectra, SNR, and derived moments, including GD and IF, varied with pressurization in the ear canal compared to measurements at ambient pressure.

The present report also describes a sidearm case study of pressurized TEOAE and reflectance measurements in an adult subject with ETD, a negative TPP, and an accompanying conductive hearing loss. In a previous study of TEOAEs recorded at ambient air pressure in the ear canal, TEOAEs generated by transient ear-canal stimuli with a constant incident pressure level across frequency were compared to TEOAEs generated by transient sounds with constant absorbed sound power across frequency (Keefe *et al.*, 2017). That study reported generally similar TEOAEs for these stimulus types in normal-hearing adults up to 8 kHz, but suggested that it would be interesting to compare TEOAEs for these stimulus types in ears with conductive-impaired middle-ear function. Following up on that suggestion, the present case study was a novel opportunity to compare TEOAEs generated using constant incident pressure and constant-power stimuli, with TEOAEs acquired at ambient pressure in the ear canal compared to TEOAEs at the TPP.

II. METHODS

A. Subjects and clinical tests

1. Subjects

Procedures for adult participants were approved by the Institutional Review Board at Boys Town National Research

Hospital. The number of participants and related data are summarized in Table I. The clinical tests included immittance at 226 Hz (GSI Tymptstar tympanometer, Eden Prairie, MN), air-conduction audiograms at octave frequencies between 0.25 and 8 kHz with additional tests at 3 and 6 kHz (GSI 61 audiometer), and bone-conduction audiograms (RadioEar, Eden Prairie, MN) at octave frequencies from 0.25 to 4 kHz. In the main experiment, data were analyzed from subjects whose clinical data satisfied the following inclusion criteria: (i) normal 226-Hz tympanometry (middle-ear pressure within ± 100 daPa and peak-compensated static admittance magnitude between 0.3 and 1.7 mmho), (ii) normal pure-tone air-conduction thresholds (25 dB hearing level or better) at frequencies from 0.25 to 8 kHz, and (3) air-bone gaps of 10 dB or less at octaves between 0.25 and 4 kHz.

A follow-up case study was performed in the right ear of subject S with ETD and an accompanying conductive hearing loss. Subject S, who is author C.A.S. in this study, is a male with a history of ETD for his right ear. He was 41 yrs old at the time that data were acquired. Subject S reported one case of otitis media with effusion 9 yrs prior to participation in the present study that was treated with antibiotics and resolved. However, following the resolution of the otitis media with effusion, the ETD did not resolve, and the subject reported persistent ETD and a slight conductive hearing loss over the past 9 yrs. The subject reported that the TPP for his right ear typically falls within a range of -110 to -120 daPa. However, at the time of testing, the subject had just completed air travel and was experiencing a more negative TPP. The subject reported an absence of sensorineural hearing loss, but the presence of a mild conductive hearing loss in the low frequencies. While air and bone conduction thresholds were not measured on the day of testing, the subject reported a history of persistent air-bone gaps of approximately 15 dB for 0.25 and 0.5 kHz, with 5 to 10 dB air-bone gaps at 1, 2, and 4 kHz.

B. General measurement procedures

The research battery included TEOAE tests and tympanometric and ambient reflectance tests. All research data were acquired using custom computer software with a two-channel sound card (CardDeluxe, Chanhassen, MN) and serial port (RS-232). Both tympanometric and TEOAE data were measured with the same insert ear probe (Titan, Interacoustics, Middelfart, Denmark). It had two receiver ports to deliver sound stimuli and one microphone port to measure acoustic pressure. The receiver generated sound stimuli under the control of the sound card with 24-bit digital-to-analog converters (DAC)1 and DAC2, and the microphone output was recorded by a 24-bit analog-to-digital converter (ADC). The sample rate per channel was 22.05 kHz for all tests. An additional port exiting the probe

tip transmitted air-pressure changes generated by the pump in the tympanometer (AT235, Interacoustics, Middelfart, Denmark, with modified firmware). A pressure sensor within the tympanometer cable measured the actual pressure, and a pressure controller circuit matched this to the desired pressure. During any pressure sweep, air pressure was varied in the ear canal, and the tympanometer communicated the measured air pressure back to the computer using the serial port.

C. Tympanometric reflectance methods

Reflectance at the probe tip was measured in response to an acoustic click over a frequency range 0.25 to 8 kHz at ambient pressure in the ear canal, and at varying air pressure between 200 and -300 daPa in down- and up-swept tympanograms using procedures described in Keefe *et al.* (2015). The peak-to-peak equivalent sound pressure level (peSPL) of the incident pressure waveform of the click was approximately 92 dB for adult ears. The absorbance is defined as one minus the squared magnitude of the pressure reflectance of the ear. During down- and up-swept tympanograms, the absorbance was measured as a joint function of frequency and pressure. A low-frequency averaged absorbance tympanogram was calculated as a function of air pressure by averaging absorbance over frequencies from 0.376 to 2 kHz in adult ears. The TPP was calculated for the down-swept tympanogram as the air pressure with the maximum low-frequency averaged absorbance. The TPP for the up-swept tympanogram was calculated in an analogous manner. The TPP of the ear was defined as the average of the TPPs from the down- and up-swept tympanograms. This average reduced any bias effects associated with the polarity of the tympanometric sweep. Normative adult data for these wideband absorbance tympanograms are available (Feeney *et al.*, 2017).

D. TEOAE methods

In tandem with other studies (Putterman *et al.*, 2017; Garinis *et al.*, 2017) using the present measurements system, the present work extended pressurized measurements of TEOAEs in adult ears up to a stimulus frequency of 8 kHz, which allowed the study of pressurization effects at higher frequencies compared to previous studies (as reviewed in Sec. I, previous studies extended to 5 kHz). This is also the first report of new pressurized TEOAE data including CSM, GD, GS, IF, and IB. Except for the added variable of air pressurization, the main experiment of the present study used the same measurement system and TEOAE methods, which are summarized below, as were described for an ambient-pressure TEOAE study (Keefe *et al.*, 2016). Receiver 1 generated wideband stimuli using DAC1, and was also used in the reflectance measurements. Receiver 2 produced higher-level signals using DAC2 that would be appropriate for acoustic stapedius muscle reflex tests (no such reflex data are reported herein), and it was also appropriate for TEOAE measurements. Both receivers and DACs were used to deliver TEOAE test stimuli, and each stimulus was calibrated to produce approximately the same acoustic waveform at a given reference level over a bandwidth from 0.71 to 8 kHz. The click and chirp stimuli each had an approximately constant incident

TABLE I. Subject inclusion.

Experiment	# Subjects			# Ears			Age (years)	
	Female	Male	Total	Left	Right	Total	Range	Mean
Adult Exp.	11	6	17	10	16	26	20–32	26

pressure spectrum level across frequency. The duration of the click stimulus buffer was 36.3 ms. The sweep rate of the “positive” chirp was 174.6 Hz/ms, so that the effective duration of the chirp to sweep from 0.71 to 8 kHz was 41.8 ms in a buffer of duration 69.7 ms. The chirp stimulus was calculated using an allpass filter of the click stimulus so that the power spectra of the click and chirp stimuli were the same.

After inserting the probe in a leak-free manner into the ear canal (or calibration coupler), the electrical input signal to DAC1 produced the transient stimulus at a reference level with measured microphone waveform $p_1[n]$ at each time sample n . The electrical input signal to DAC2 produced the substantively identical transient stimulus at a level 12 dB above this reference level with measured microphone waveform $p_2[n]$. A microphone waveform $p_{12}[n]$ was recorded in response to the simultaneous presentation of the electrical input signals to DAC1 and DAC2. A double-evoked procedure was used to extract a nonlinear TEOAE waveform from these three pressure measurements to transient stimuli, in particular, the nonlinear residual pressure waveform $p_d[n]$ of the TEOAE was calculated using (Keefe, 1998; Keefe and Ling, 1998)

$$p_d[n] = p_1[n] + p_2[n] - p_{12}[n]. \quad (7)$$

The electrical input signals to generate $p_1[n]$, $p_2[n]$, and $p_{12}[n]$ were synchronously output over a nominal measurement duration of 1 min, and their responses were stored in multiple response buffers. The desired number of response buffers in one minute was $K = 552$ for the click stimulus and $K = 288$ for the chirp stimulus. These values for K correspond to a nominal TEOAE test duration of 1 min for both click and chirp types of TEOAEs. Data were highpass filtered in real time with 3-dB down frequency of 0.66 kHz to exclude low-frequency noise, and calibrated for frequency variations in microphone sensitivity. TEOAEs were elicited by stimuli at two mean reference levels differing by 6 dB as further described in Sec. III.

These reference DAC levels were adjusted in long-tube recordings at ambient air pressure to avoid any stimulus distortion in the measurement system, according to procedures described in Keefe *et al.* (2016). Briefly, the measurement in the long tube allowed extraction of the incident pressure response to each stimulus, and the maximum DAC levels of the stimuli were set such that no distortion was detected with respect to the noise present in a 1-min measurement. Each of the DAC1 and DAC2 levels was reduced in all ear measurements by at least 9 dB relative to maximum tube levels. Ear-canal standing waves might increase the sound levels by 6 dB at the microphone location, and an additional 3 dB of attenuation was added for possible variations between ears.

A median absolute deviation test was used with the cumulative dataset during data acquisition to identify and exclude outliers in the response buffers relative to the medians of the peak-to-peak amplitude, crest factor, and noise energy. This test was performed every 6 s during data acquisition using the cumulative dataset to provide feedback to the operator of the cumulative average TEOAE response, and additional trials were added at the end of the test so that the final dataset included 1 min of artifact-free data.

For click TEOAE data, each ADC buffer was assigned to one of a set of $L = 24$ averaging blocks, such that each successive response buffer was placed in a different block than the preceding response buffer. Once all buffers were assigned to some block, the time average of the responses in each block was calculated as a coherent average across blocks. For chirp TEOAE data, each ADC buffers was assigned to one of a set of $L = 16$ blocks and similarly averaged. TEOAE signal and noise pressure spectra were calculated across the L blocks of windowed waveforms using coherent and incoherent averaging (Goodman *et al.*, 2009), such that the incoherent average provided the estimated noise level. A multi-window spectrum and temporal analysis of the TEOAE residual waveform was performed that improved the overall SNR of the TEOAE by 5–6 dB (Keefe *et al.*, 2016).

Equivalent-click pressure waveforms were calculated for each of the measured $p_1[n]$, $p_2[n]$, and $p_{12}[n]$ waveforms of the chirp response by filtering the data using the inverse of the allpass filter used to generate the chirp stimuli from the click stimuli. Whether for click or chirp stimuli, the measured TEOAE was analyzed in terms of the click or equivalent-click response in Eq. (7).

The sound exposure level (SEL), which is defined below, quantified the sound level of each transient sound, and the SEL spectrum represented the integrated band SEL at each center half-octave frequency of the spectrum. Following Keefe *et al.* (2016), the sound exposure E of a pressure waveform $p[n]$ at sample n with sample period T and sample duration N is

$$E = T \sum_{n=0}^{N-1} p[n]^2. \quad (8)$$

The total SEL of this waveform is defined in terms of a reference time $T_{\text{ref}} = 1$ s and the reference root mean squared pressure $p_{\text{ref}} = 20 \mu\text{Pa}$ by

$$\begin{aligned} \text{SEL} &= 10 \log_{10} \left(\frac{E}{T_{\text{ref}} p_{\text{ref}}^2} \right) \\ &= 10 \log_{10} \left(\frac{T}{NT_{\text{ref}} p_{\text{ref}}^2} \left(\sum_{k=1}^{N/2-1} 2|P[k]|^2 \right. \right. \\ &\quad \left. \left. + |P[0]|^2 + |P[N/2]|^2 \right) \right). \end{aligned} \quad (9)$$

The bottom relation is expressed in terms of the complex pressure spectrum $P[k]$, which is calculated as the N -sample discrete Fourier transform of $p[n]$ at the k th frequency $f_k = k/(NT)$, such that k ranges from 0 to $N/2$ for even N . A frequency-averaged integrated band sound-pressure level $\langle L_{\text{Eb}} \rangle$ is defined as an average level over a frequency band between $k_1 > 0$ and $k_2 \geq k_1$ (and $k_2 < N/2$) by

$$\begin{aligned} \langle L_{\text{Eb}}(k_1, k_2) \rangle &= 10 \log_{10} \left(\frac{T}{NT_{\text{ref}} p_{\text{ref}}^2} \frac{1}{(k_2 - k_1 + 1)} \right. \\ &\quad \left. \times \sum_{k=k_1}^{k_2} 2|P[k]|^2 \right). \end{aligned} \quad (10)$$

The frequency bands from k_1 to k_2 were chosen to match a given half-octave average to smooth effects of TEOAE fine structure and noise. The $\langle L_{Eb} \rangle$ in Eq. (10) is termed the *SEL spectrum* in this report.

The additional procedures for the tympanometric TEOAE test are as follows. The TPP was measured in each ear based on the low-frequency averaged absorbance tympanogram. Pressurized TEOAEs were measured for each stimulus type (click, chirp) at the individual TPP of each ear, and at four other air pressures in the ear canal of -200 , -100 , 100 , and 150 daPa. The nominal test duration at each air pressure value was 1 min, the same as for the ambient-pressure test. This range of pressures covered a substantial part of the range of pressures used in tympanometry, although the maximum pressure was limited to 150 daPa to avoid problems of air leaks between the probe and ear canal during the 1-min TEOAE test. For each desired air pressure, the actual air pressure was monitored at 25 ms intervals during the test, and the test was automatically paused if the desired and actual pressures differed by more than 10 daPa. During such a pause, the operator was alerted to check the quality of the probe fit and restart the test at the beginning of the test or at the beginning of the most recent 6-s recording interval. The stored TEOAE data at a fixed air pressure were otherwise analyzed in the same manner as the TEOAE at ambient pressure.

The output voltage levels of the DACs used to generate sound stimuli to elicit pressurized TEOAEs were the same as for the ambient-pressure TEOAE recordings. Because of the limited capacity of the tympanometric pump, it was not possible to pressurize the long tube (coiled length of 30.5 m and circular cross-sectional area of 0.495 cm^2), which was used to assess distortion in the ambient-pressure measurements. Notwithstanding that fact, measurements in smaller cavities (e.g., a cylindrical cavity of length 8.2 cm and cross-sectional area 0.495 cm^2) were used to verify that distortion was absent, i.e., below the residual measurement-noise levels in a 1-min measurement.

E. Additional methods in case study

In the case study of subject S with ETD, an ambient reflectance test was performed to measure the sound power spectrum $W[k]$ absorbed by the ear at the k th frequency. The procedures to measure $W[k]$ followed Keefe *et al.* (2017). The acoustic conductance $G[k]$ is the real part of the measured acoustic admittance at the probe tip. $W[k]$ was calculated in terms of the complex pressure spectrum $P[k]$ at the probe tip as

$$W[k] = \frac{1}{2} G[k] |P[k]|^2, \quad (11)$$

and expressed as an absorbed sound power spectrum level L_W by

$$L_W[k] = 10 \log_{10}(W[k]/W_0), \quad (12)$$

in which the reference value for absorbed power is $W_0 = 4 \times 10^{-18}$ Watt. This value was selected so that $L_W[k] = 0$ dB for a sound pressure spectrum level $L_P[k]$ of 0 dB

SPL delivering power into a conductance of 1 mmho (i.e., 0.001 mho CGS). In a conductive-impaired ear such as this ear with ETD, the acoustic conductance and pressure at the probe tip differ from that of an ear with normal middle-ear function. A result is that the absorbed sound power differs in a conductive-impaired ear from that of a normal ear. Moreover, the fact that the ear had a negative TPP meant that the properties of the sound stimuli and the resulting TEOAE generated using those stimuli would vary according to the air pressure in the ear canal in a manner that would likely be different from the pressure variation of TEOAEs in the ears with normal function. In particular, TEOAEs recorded at the TPP in this ear may be more similar to a typical range of TEOAEs in ears with normal function than TEOAEs recorded in this ear at ambient pressure.

Based on the original chirp stimuli with an approximately constant incident SPL across frequency and the measured conductance, new chirp stimuli were calculated for use with DAC1 and DAC2 to generate sound spectra with approximately constant levels of absorbed sound power across frequency (Keefe *et al.*, 2017). The sound stimuli with constant incident SPL across frequency or constant absorbed sound power level across frequency partially controlled for the presence of ear-canal standing waves at higher frequencies.

Both ambient and tympanometric TEOAE tests were performed as in the main experiment using a chirp stimulus with approximately constant incident pressure level across frequency. In particular, the tympanometric TEOAE test was performed at the TPP inferred from the measurement of a wideband reflectance tympanogram. Tympanometric and ambient TEOAE tests were also performed using a chirp stimulus with approximately constant absorbed sound power level across frequency.

III. RESULTS

Results are presented in the main experiment for the group of 26 normal-hearing adult ears described in Table I. The measured TPP from the down- and up-swept absorbance tympanograms ranged from -48 to 48 daPa, with all but the two extremal values of TPP lying between -25 and 20 daPa. The mean TPP was 2.7 daPa with a standard error (SE) of the mean of 3.6 daPa. Thus, the mean TPP was close to ambient pressure.

A. Click TEOAEs

For the TEOAE measurement at the TPP, Fig. 1 shows the mean (± 1 SE) stimulus spectra (top panels) and TEOAE spectra (bottom panels) for the click stimulus condition at the lower (left panels) and higher (right panels) stimulus levels. The individual curves in each panel show data at the TPP, and also at fixed air pressures of -200 , -100 , 100 , and 150 daPa. The top panel titles in this and subsequent figures show the mean SEL and mean peSPL for the stimulus presented at the TPP, with 6 dB larger levels on the right. The mean variations in stimulus SEL spectrum level across pressure conditions were relatively small relative to their SEs. The bottom panels show the mean TEOAE SEL spectrum levels as a function of frequency across the pressure conditions. The mean variations

FIG. 1. (Color online) Mean ± 1 SE of SEL spectra vs frequency at fixed air pressures in ear canal. (A) Click stimulus at lower SEL (33.7 dB). (B) Click stimulus at higher SEL (39.7 dB). (C) Click TEOAE at lower SEL. (D) Click TEOAE at higher SEL. In this and subsequent figures, the data are slightly offset horizontally to assist in visualizing each curve.

of the TEOAE spectrum level across pressure conditions remained relatively small relative to their SEs, although there was slightly less overlap in the range of TEOAE levels relative to the stimulus levels. The main feature evident in Fig. 1 is the pattern of the stimulus and TEOAE level spectra across frequency. The stimulus level had a relative minimum near 2.8 kHz, i.e., close to a so-called “quarter-wavelength resonance frequency” based on the distance between the probe tip and the tympanic membrane, and approached a relative maximum near, or possibly just above, 8 kHz (i.e., close to a so-called “half-wavelength” resonance frequency). These properties of ear-canal acoustics are described in the context of stimuli used to elicit OAEs in [Souza et al. \(2014\)](#) and [Keefe et al. \(2017\)](#). The mean TEOAE level had a lowpass shape across frequency with the largest levels below 1 kHz and only small variations between 2.8 and 8 kHz.

Figure 2 shows TEOAE level differences across pressure conditions at each half-octave frequency. The level difference Δ SEL was calculated for each ear as the change in the TEOAE SEL spectrum in each pressurized condition relative to the TEOAE SEL spectrum at ambient ear-canal pressure. The mean ± 1 SE of Δ SEL across all ears are plotted for the lower click stimulus level in the top panel of Fig. 2, and for the higher click stimulus level in the bottom panel. Each curve represents the change in TEOAE level at one frequency as a function of air pressure in the ear canal, with curves displayed on the left for half-octave frequencies between 0.7 and 2 kHz, and on the right for frequencies

between 2.8 and 8 kHz. The SEs were small, on the order of 0.1–0.2 dB, except for larger SEs near 0.4 dB at 8 kHz for pressures of –200 and –100 daPa.

The mean Δ SEL data between TEOAEs measured under TPP and ambient conditions were within 1 dB at all frequencies and stimulus levels. The main contributing factor to this similarity was the inclusion criteria, which required that the TPP of all ears be within ± 100 daPa and, in fact, the measured TPP was usually close to 0 daPa. For TEOAEs at fixed air pressures, the mean level was reduced by 2–3 dB at 1 and 1.4 kHz at the lower stimulus level, and by 2.5 to 4 dB at 0.7 to 2.8 kHz at the higher stimulus level. This reduction was larger at the largest relative air pressures (–200 and 150 daPa), although the reductions at these frequencies were generally similar to those at 100 daPa. These mean level changes with air pressure (other than at TPP) were larger by about an order of magnitude than their corresponding SEs. At frequencies up to 2.8 kHz, pressurization in the tympanometric range attenuated TEOAE levels relative to the ambient condition. This finding is consistent with earlier studies described in Sec. I.

The mean Δ SEL generally increased with increasing air pressure at frequencies between 4 and 8 kHz, although the magnitude differences were within 1 dB at pressures of 100 and 150 daPa. A mean reduction on the order of 2 to 2.5 dB was observed at 8 kHz for –200 daPa condition. The mean Δ SEL at the lower stimulus level at the lowest TEOAE frequency of 0.7 kHz was close to –1 dB at all pressures. The

FIG. 2. (Color online) Mean ± 1 SE of difference Δ SEL in the click SEL spectra vs air pressure in the canal at fixed frequencies, relative to the SEL spectrum at ambient pressure in the ear canal. (A) Δ SEL at lower frequencies at lower SEL. (B) Δ SEL at higher frequencies at lower SEL. (C) Δ SEL at lower frequencies at higher SEL. (D) Δ SEL at higher frequencies at higher SEL.

mean Δ SEL was reduced at both positive and negative air pressures at frequencies of 1 and 2 kHz. These mean shifts were also large compared to their respective SEs.

Across all ears, Fig. 3 shows the mean CSM and SNR of the click TEOAE versus frequency at the lower-level (top row) and higher-level (bottom row) stimulus conditions. The critical CSM and SNR are plotted as a dotted line in each panel. When averaged across all ears, the TEOAE at the lower stimulus level was classified as present based on the mean CSM [Fig. 3(A)] across most pressures at 4–8 kHz, and absent for $f \leq 2$ kHz, with ambiguous classification at 2.8 kHz. The TEOAE was classified as present based on mean SNR [Fig. 3(B)] across most pressures at 4–5.7 kHz, and absent for $f \leq 2$ kHz, with ambiguous classification at 2.8 and 8 kHz. At the higher level, the TEOAE was classified as present based on the mean CSM [Fig. 3(C)] across most pressures at 2.8–8 kHz, and absent at most pressures for $f \leq 1$ kHz, with ambiguous classification at 1.4–2 kHz. The TEOAE was classified as present based on the mean SNR [Fig. 3(D)] across pressure at 4–8 kHz, and absent for $f \leq 1.4$ kHz, with ambiguous classification at 2–2.8 kHz. These results showed that the mean CSM and SNR increased with increasing stimulus level, as expected, so that their

mean values at the higher stimulus level exceeded their critical values across a wider frequency range. The mean CSM and SNR trended to slightly smaller values across frequency at the extremal pressures (–150 and 200 daPa).

Figure 4 shows the mean CSM and SNR of the click TEOAE versus time at the lower level (top row) and higher level (bottom row). The critical CSM and SNR are plotted as a dotted line in each panel. At the lower level, the TEOAE was classified as present based on mean CSM [Fig. 4(A)] across most pressures at $t \leq 2$ ms, and absent for $t \geq 8$ ms, with ambiguous classification at times from 2.8–5.7 ms. The TEOAE was classified as present based on mean SNR [Fig. 4(B)] across most pressures at 1.4–4 ms, and absent for $t \geq 8$ ms, with ambiguous classification at 0.7, 1, and 5.7 ms. At the higher level, the TEOAE was classified as present based on mean CSM [Fig. 4(C)] across most pressures at 0.7–5.7 ms, and absent at most pressures for $t \geq 8$ ms. The TEOAE was classified as present based on mean SNR [Fig. 4(D)] across pressure at 0.7–4 ms, and absent for $t \leq 11.3$ ms, with ambiguous classification at 5.7–8 ms. These results show that the mean CSM and SNR increased with increasing stimulus level, so that their mean values exceeded in their critical values across a wider temporal range.

FIG. 3. (Color online) Mean ± 1 SE of click TEOAE CSM and SNR vs frequency at fixed air pressures in the ear canal. (A) CSM at lower SEL. (B) SNR at lower SEL. (C) CSM at higher SEL. (D) SNR at higher SEL.

As explained in Sec. II, the GD or IF was calculated from TEOAE phase data only if its CSM exceeded its critical value in the frequency or time domain, respectively. The GS or IB was calculated from TEOAE level data only if its SNR exceeded its critical value in the frequency or time domain, respectively. Not all ears reached their criterion values of CSM and SNR at all frequencies and all times. For example, the mean CSM and SNR values in Figs. 3(A) and 3(B), respectively, were below their respective criterion values for frequencies at and below 2 kHz across all pressure conditions. In the same panels, the range of CSM and SNR values quantified by ± 1 SE straddled their respective criterion values at 8 kHz. Figure 5 shows the mean ± 1 SE of each of the TEOAE moments for those ears that did satisfy these criteria. Results are shown only for click TEOAEs at the higher stimulus level, at which GD, GS, IF, and IB were calculated for more test ears than for TEOAEs at the lower level.

The mean (SE) of GD for the click TEOAE are shown as a function of frequency in Fig. 5(A) for each pressurized condition. The number of test ears at each frequency based on CSM at each frequency is shown in the bottom of the panel, such that no mean data are plotted if the number of test ears with a detected TEOAE was less than 2. The dotted line shows the predicted TEOAE GD proportional to $1/f$ for a scale-symmetric cochlea (Sisto *et al.*, 2007), which passes through a typical adult value of 11 ms at 1 kHz. The measured GDs were slightly larger than this predicted GD with a similar slope at frequencies up to 4 kHz, and more elevated

values at 5.7 and 8 kHz. The differences in mean GD across pressure conditions were small relative to their SEs at all frequencies, although the SEs increased at 5.7–8 kHz. The CSM reached criterion at fewer ears for $f < 2.8$ kHz than at higher frequencies.

The mean GS data of the click TEOAE are shown as a function of frequency in Fig. 5(B) for each pressurized condition along with the number of ears listed at the top of the panel with a TEOAE present based on SNR. The differences in mean GS across pressure conditions were small relative to their SEs at all frequencies, except for a trend to a relatively larger mean GS at the extremal air pressure of -200 daPa.

The mean IF data of the click TEOAE are shown as a function of time in Fig. 5(C) for each pressurized condition along with the number of ears listed at the bottom of the panel with a TEOAE present based on CSM at each time step. The dotted line shows the predicted TEOAE IF proportional to $1/t$ for a scale-symmetric cochlea (Keefe, 2012; Keefe *et al.*, 2016), which would intersect a typical adult value of 11 kHz at 1 ms (not shown). At times ranging from 2 to 8 ms, the mean IF are slightly elevated at the positive air pressures of 100 and 150 daPa relative to the means at TPP and at negative pressures. This is evidence for a pressurization effect on transmission through the ossicular chain.

The mean IB data of the click TEOAE are shown as a function of time in Fig. 5(D) for each pressurized condition along with the number of ears listed at the bottom of the panel with a TEOAE present based on SNR at each time step. The differences in mean IB across pressure conditions

FIG. 4. (Color online) Mean ± 1 SE of click TEOAE CSM and SNR vs time at fixed air pressures in the ear canal. (A) CSM at lower SEL. (B) SNR at lower SEL. (C) CSM at higher SEL. (D) SNR at higher SEL.

were small relative to their SEs at most times, except that the mean IB at 2 ms was smaller at the positive air pressures of 100 and 150 daPa compared to the mean IB at TPP and negative pressures. The apparently lower mean IB at TPP at 11.3 ms is of little interest, as the mean at that time was calculated using data from only two ears.

The frequency dependences of GD and GS and the time dependences of IF and IB for the pressurized click TEOAEs were similar to those of the corresponding moments of the ambient click TEOAEs (Keefe, 2012; Keefe *et al.*, 2016). Although not shown, the stimulus level dependence of each moment of the click TEOAE across pressure conditions was similar to the level dependence for click TEOAEs at ambient pressure described in Keefe (2012), e.g., GD and IF were reduced at increased stimulus levels.

B. Chirp TEOAEs

TEOAEs elicited by a positive chirp at two stimulus levels differing by 6 dB were also measured across the same pressurization conditions. A difference between the click and chirp stimuli was that the mean SEL of the chirp and the peSPL of the chirp in the equivalent-click representation were larger than those for the click stimuli (as described below). This may be a practical advantage in using chirps to elicit TEOAEs, as larger stimulus energies are obtained for chirps than for clicks when compared at similar peSPLs. The onset of distortion in the sources of transient sounds used in OAE probes is closely related to a criterion value of peSPL,

so that the maximum SEL attainable with clicks is smaller than that attainable with chirps.

The mean and SE of the chirp stimulus spectra and evoked TEOAE spectra are not plotted as they were generally similar to those shown for the click TEOAE in Fig. 1. This similarity replicated findings for click and chirp TEOAEs at ambient air pressure (Keefe *et al.*, 2016). Other types of TEOAE responses are described next that were more sensitive to the TEOAE differences between click and chirp stimulus conditions.

The level difference Δ SEL was calculated for each ear as the change in the chirp stimulus SEL spectrum in each pressurized condition relative to that at ambient ear-canal pressure. The mean ± 1 SE of Δ SEL across all ears is plotted for TEOAEs at the lower chirp stimulus level in the top panel of Fig. 6, and at the higher chirp stimulus level in the bottom panel. At each of the lower stimulus levels, the chirp stimulus SEL was 41.8 dB while the click stimulus SEL was 33.7 dB (see Fig. 6), or 8.1 dB higher for the chirp. Despite this larger SEL, the peSPL of the chirp stimulus was only 62.5 dB compared to a peSPL of 67.0 dB for the click stimulus, i.e., the peSPL was reduced by 4.5 dB in the chirp. When normalized to the same peSPL, the chirp SEL would be about 12.6 dB higher than the click SEL. This same benefit was obtained by comparing chirp and click stimuli at each of their higher stimulus levels. This quantifies the advantage of using chirps when the goal is to increase the stimulus level to more easily detect an OAE in noise. Longer-duration

FIG. 5. (Color online) Mean ± 1 SE of click TEOAE moments (smoothed) at fixed air pressures in the ear canal, and at higher SEL of 39.7 dB. (A) GD vs frequency. (B) GS vs frequency. (C) IF vs time. (D) IB vs time. The number of test ears is shown at each frequency based on CSM in (A) and SNR in (B), and at each time based on CSM in (C) and SNR in (D).

chirps normalized to the same peSPL would increase this benefit.

The pattern of mean Δ SEL results for chirp TEOAEs at the higher stimulus level [see Figs. 6(C) and 6(D)] was similar to the corresponding results for click TEOAEs [compare to Figs. 2(C) and 2(D)]. A minor difference was that the mean Δ SEL was slightly reduced at 150 daPa for the chirp TEOAEs compared to the click TEOAEs at frequencies from 0.7 to 2.8 kHz. This cannot be easily interpreted because of the difference in the stimulus SEL in the two stimulus conditions. As for Δ SEL of the click TEOAEs, the mean chirp Δ SEL data between TPP and ambient conditions were within 1 dB at all frequencies and stimulus levels.

In the frequency domain, the CSM and SNR of TEOAEs elicited by clicks (in Fig. 3) and chirps (in Fig. 7) increased with increasing signal level across the pressure conditions at higher frequencies ($f \geq 2.8$ kHz) at which CSM and SNR exceeded their respective critical values. This finding is the expected result for a cochlea with nonlinear compressive mechanics. The level difference was smaller or not observed at lower frequencies (0.7 to 2 kHz), in part, because the response was more dominated by noise in the absence of a TEOAE response.

In the time domain, the CSM and SNR of TEOAEs elicited by clicks (in Fig. 4) and chirps (in Fig. 8) increased with increasing signal level across the pressure conditions at shorter times ($t \leq 4$ ms) at which CSM and SNR exceeded

their respective critical values (in dotted lines). This also is an expected result for a nonlinear cochlea. The level difference was smaller or not observed at larger times (above 5.7 ms), in part, because the response was more dominated by noise.

As in calculations of the click TEOAE moments, each chirp TEOAE moment in each ear was calculated only if the CSM or SNR exceeded a critical value. Figure 9 shows the mean ± 1 SE of each of the signal processing moments of the chirp TEOAEs measured at the lower stimulus level. The mean (and SE) of GD for the chirp TEOAE are shown as a function of frequency in Fig. 9(A) for each pressurized condition. Results are shown only for chirp TEOAEs at the lower stimulus level (SEL = 41.8 dB), which was slightly larger by 2.1 dB compared to the stimulus SEL for the click TEOAE responses. The number of test ears at each frequency based on CSM at each frequency is shown in the bottom of Fig. 9(A). The measured GDs were slightly larger than the predicted GD (based on cochlear scale symmetry) at $f \leq 2.8$ kHz, and more elevated at higher frequencies. The differences in mean GD across pressure conditions were smaller than, or on the order of, their SEs at all frequencies. The CSM reached criterion at fewer ears for $f < 2.8$ kHz than at higher frequencies. For GD (and correspondingly for other moments), the underlying CSM and SNR attained their critical values in fewer ears for the chirp TEOAE than the click TEOAE.

FIG. 6. (Color online) Mean ± 1 SE of difference Δ SEL in the chirp SEL spectra vs air pressure in the canal at fixed frequencies, relative to the SEL spectrum at ambient pressure in the ear canal. (A) Δ SEL at lower frequencies at lower SEL. (B) Δ SEL at higher frequencies at lower SEL. (C) Δ SEL at lower frequencies at higher SEL. (D) Δ SEL at higher frequencies at higher SEL.

The mean GS data of the chirp TEOAE are shown as a function of frequency in Fig. 9(B) for each pressurized condition along with the number of ears listed at the top of the panel with a TEOAE present based on SNR. The differences in mean GS across pressure conditions were small relative to their SEs at most frequencies. The exception occurred at 5.7 kHz, in which the mean GS at negative air pressures was larger than that at positive air pressures, with an intermediate value for GS at TPP (that was close to ambient pressure). This exception at 5.7 kHz was not observed for the GS of the click TEOAE [compare to Fig. 5(B)].

The mean IF data of the chirp TEOAE are shown as a function of time in Fig. 9(C) for each pressurized condition along with the number of ears listed at the bottom of the panel with a TEOAE present based on CSM at each time step. The mean IF data were generally similar across the pressure conditions at the times for which the mean IF was calculated (i.e., from 0.7 to 5.7 ms). There was a slight trend in the chirp TEOAE data for larger mean IF at the largest positive pressure of 150 daPa, but this mean difference was less than that found for IF in the click data [compare to Fig. 5(C)], e.g., at 2.8 ms.

The mean IB data of the chirp TEOAE are shown as a function of time in Fig. 9(D) for each pressurized condition

along with the number of ears listed at the bottom of the panel with a TEOAE present based on SNR at each time step. The differences for the chirp TEOAE in mean IB across pressure conditions were small relative to their SEs at most times, with a similar temporal pattern as that found for mean IB for the click TEOAE [compare to Fig. 5(D)].

Although not shown, the stimulus level dependencies of the chirp TEOAE moments across pressure conditions were similar to the level dependence for ambient-pressure click TEOAE moments (Keefe, 2012), and for GD and GS data reported for ambient-pressure chirp TEOAEs (Keefe *et al.*, 2016). As described in the 2012 article, this level dependence of TEOAE moments is consistent with the compressive nonlinearity of the outer hair cell function.

C. Comparing TEOAEs for click and chirp stimuli having similar SELs

While TEOAEs were acquired at two levels for each of the click and chirp stimulus types, the means of their (in-the-ear) SELs were similar in only one pair of responses. The higher-level click had a mean SEL of 39.7 dB. This SEL is referred to as the reference level and was the maximum

FIG. 7. (Color online) Mean ± 1 SE of chimp TEOAE CSM and SNR vs frequency at fixed air pressures in the ear canal. (A) CSM at lower SEL. (B) SNR at lower SEL. (C) CSM at higher SEL. (D) SNR at higher SEL.

possible SEL for the click stimulus to avoid distortion. The lower-level chirp had a mean SEL of 41.8 dB. Thus, the mean chirp SEL was only 2.1 dB larger than the click SEL. Such a difference in stimulus level would produce even smaller differences in TEOAE responses generated by the compressive nonlinearity of cochlear mechanics. Thus, this chirp SEL was classified as a satisfactory approximation to the reference level for purposes of comparisons.

The differences in the mean SNR and CSM (Δ SNR and Δ CSM, respectively) at each frequency and time step, and at each pressure, were calculated as the chirp response minus the click response at the reference level. The SE of each difference response was calculated as the square of the sum of the squares of the SEs of the click and chirp responses. Figure 10 shows the comparison of the mean Δ SNR and Δ CSM versus frequency and time. Overall, the mean Δ SNR and Δ CSM remained close to the null condition across frequency (top panels), although their means tended to be slightly positive (i.e., larger for chirps) at the most negative pressure (−200 daPa) and slightly negative at the most positive pressure (150 daPa). The mean Δ SNR at all pressures were most different from the null condition at 1 kHz relative to the range ± 1 SE. The mean Δ SNR and Δ CSM remained close to the null condition across time (bottom panels), except that mean Δ CSM was negative for all pressures at 1.4 ms, and had a relative maximum with positive means at 2.8 ms. The mean Δ SNR curves across time were generally similar in having a minimum near 1.4 ms and maximum at 2.8 ms or later times. The

mean Δ SNR at the largest pressure 150 daPa was more negative than at smaller pressures for short times (0.7–1.4 ms).

For the click and chirp stimuli at their reference level, the differences in the mean GD and GS (Δ GD and Δ GS, respectively) at each frequency and each pressure, were calculated as the chirp response minus the click response. The SEs of Δ GD and Δ GS were calculated as above, i.e., as the square root of the sum of squares of the SEs for the click and chirp responses. The mean Δ GD and Δ GS were present at all frequencies between 2 and 8 kHz in the top panels of Fig. 11. The mean Δ GD increased with increasing frequency from about −3.5 ms at 2 kHz depending on the particular pressure condition to about 0 ms at 8 kHz, with values in the range of −1 to 0 ms at 8 kHz. Thus, the GD of the chirp TEOAE was less than the GD of the click TEOAE, and especially so at lower frequencies. The mean Δ GS ranged across pressures and frequencies from −1 ms up to −0.2 ms, i.e., GS was smaller for the chirp than the click TEOAE. These shifts are also evident by comparing GD and GS responses in the upper panels of Fig. 5 for the click and Fig. 9 for the chirp.

These shifts of mean Δ GD and Δ GS in pressurized TEOAEs between the click and chirp stimulus conditions are similar in magnitude to those inferred from the mean GD and GS data reported for ambient-pressure TEOAEs between the click and a so-called “positive chirp” stimulus type in Fig. 10 of Keefe *et al.* (2016).

For the click and chirp stimuli at their reference level, the differences in the mean IF and IB (Δ IF and Δ IB,

FIG. 8. (Color online) Mean ± 1 SE of chirp TEOAE CSM and SNR vs time at fixed air pressures in the ear canal. (A) CSM at lower SEL. (B) SNR at lower SEL. (C) CSM at higher SEL. (D) SNR at higher SEL.

respectively) at each time and each pressure, were calculated as the chirp response minus the click response, and their SEs were calculated in a similar manner as above. The mean Δ IF and Δ IB were present at all times between 0.7 and 5.7 ms, and Δ IB was also present at 8 ms in the bottom panels of Fig. 11. The mean deviations of Δ IF and Δ IB from 0 Hz were generally of the same order of magnitude as ± 1 SE from the mean, with the exception that the mean Δ IF was slightly positive for all the pressure conditions in the range of 0.5–0.8 kHz at times of 2–2.8 ms. Although not commented on in the ambient-pressure IF and IB data in Fig. 11 of Keefe *et al.* (2016), the maximum difference in mean IF between the positive chirp and click TEOAEs occurred with a value around 0.4 kHz at 2.8 ms that was larger than their SEs. This is quantitatively similar to the present tympanometric data for Δ IF. Both studies showed a mean Δ IB close to 0 kHz.

The similarity between tympanometric and ambient-pressure measurements of the mean differences in each of the TEOAE moments (between click and chirp conditions) is evidence of the underlying similarity between the cochlear mechanisms of TEOAE production. With the exception noted above (i.e., Δ SNR for the 150 daPa pressure condition at times between 0.7 and 1.4 ms), the pressurized TEOAEs in normal ears were similar to ambient-pressure TEOAEs. After adjusting for the 2.1 dB difference in reference levels, the click and chirp stimuli differed only in their phase spectra. There was consistency between the present tympanometric

data and previous ambient-pressure data about the frequencies at which the mean Δ GD and Δ GS differed from 0 ms, and the times at which the mean Δ IF differed from 0 kHz. These deviations from the null condition are evidence of spatial-temporal differences in the nonlinear mechanics on the basilar membrane in response to differences in stimulus phase, as further described for ambient-pressure TEOAEs in Keefe *et al.* (2016).

D. Case study in subject with ETD

The tympanometric reflectance for the right ear of subject S with ETD had a TPP of -165 daPa (this was the TPP averaged over the down- and up-swept tympanograms). This TPP was much more negative than the TPPs permitted for inclusion in the normal-hearing group in the main experiment, for which the TPP was required to lie within ± 100 daPa. Figure 12(A) shows the sound pressure spectrum levels L_p for the ambient reflectance test compared to the tympanometric reflectance test at the TPP, the most positive-tail pressure of $P_{pt} = 200$ daPa, and the most negative-tail pressure of $P_{nt} = -300$ daPa. The L_p was smaller at frequencies up to 1.4 kHz in the TPP condition compared to the ambient condition and the tail-pressure conditions (P_{pt} and P_{nt}). Despite the negative TPP, the L_p at the tail pressures were similar to one another.

The measured absorbed sound power spectrum level L_W in Fig. 12(B) showed more pronounced differences between pressure conditions. The L_W was 5–6 dB larger for the TPP

FIG. 9. (Color online) Mean ± 1 SE of chirp TEOAE moments (smoothed) at fixed air pressures in the ear canal, and at lower stimulus SEL of 41.8 dB. (A) GD vs frequency. (B) GS vs frequency. (C) IF vs time. (D) IB vs time. The number of test ears are shown at each frequency based on CSM in (A) and SNR in (B), and at each time based on CSM in (C) and SNR in (D).

than the ambient condition at frequencies between 0.25 and 2.8 kHz, and smaller between 4 and 8 kHz. At lower frequencies up to 2.8 kHz, the L_W for the negative TPP condition was more similar to the Pnt than the Ppt condition, which would be expected due to the fact that the TPP and Pnt pressures were more similar. The L_W was reduced at the positive-tail condition compared to all other conditions at frequencies up to 2.8 kHz, and, in particular, it was reduced compared to the ambient condition. The general effect in this ear at these low-to-moderate frequencies is that the negative middle-ear pressure reduced the absorbed sound power at ambient pressure, or at the tail pressures, relative to the sound power at the TPP. These functional differences in the ability of the middle ear to absorb sound power were revealed more clearly in the power level measurement than in the pressure level measurement. Differences across air-pressure conditions in the ear canal were also pronounced in reflectance and admittance responses, both at the probe tip and estimated as an equivalent admittance at the tympanic membrane (data not shown).

The TEOAE CSM and SNR measured for the right ear of subject S under both ambient and pressurized (at the TPP) conditions are shown in Fig. 13. Each panel shows results for TEOAEs measured using stimuli with constant incident pressure magnitude across frequency and constant absorbed sound power across frequency. Relative to the critical values of CSM and SNR, the TEOAEs were typically classified as present from 0.7 kHz up to 4 kHz, and absent at 5.7–8 kHz.

An exception to this classification occurred for the power-weighted stimulus at ambient condition for which the TEOAE was absent based on CSM at 0.7 kHz and absent based on SNR at 0.7–1 kHz. Another borderline exception at 5.7 kHz was that the incident-weighted stimulus at ambient produced a detected TEOAE based on CSM that was absent based on SNR.

Comparing ambient and pressurized TEOAEs generated using the incident-weighted stimulus, both CSM and SNR were larger at TPP than at ambient between 0.7 and 2.8 kHz, and smaller between 4 and 8 kHz. This appeared to be a slight advantage for the TEOAE at TPP inasmuch as the emission was absent or borderline at 5.7 and 8 kHz (with the exception already noted). The finding that the TEOAE CSM and SNR were larger in the ambient than the TPP condition at 4 kHz is consistent with the slightly larger L_P and L_W in Fig. 12. Comparing ambient and pressurized TEOAEs generated using the power-weighted stimulus, the CSM and SNR were substantially larger when measured at the TPP relative to the ambient condition at all frequencies at which the TEOAE was classified as present (0.7 to 4 kHz). Overall, the measured TEOAEs were more robust when measured at the TPP, which equalized the pressure across the tympanic membrane, than at ambient pressure.

IV. DISCUSSION

In the TEOAE test in normal adult ears with ear-canal pressurization to the individual TPP in each ear, the resulting

FIG. 10. (Color online) Mean ± 1 SE of TEOAE changes ΔCSM and ΔSNR as measured using chirp compared to click stimuli at fixed air pressures in the ear canal, and at the reference stimulus SEL (39.7 dB for clicks and 41.8 dB for chirps). (A) ΔCSM vs frequency. (B) ΔSNR vs frequency. (C) ΔCSM vs time. (D) ΔSNR vs time.

FIG. 11. (Color online) Mean ± 1 SE of changes in TEOAE moments (smoothed) as measured using chirp compared to click stimuli at fixed air pressures in the ear canal, and at reference stimulus SEL (39.7 dB for clicks and 41.8 dB for chirps). (A) ΔGD vs frequency. (B) ΔGS vs frequency. (C) ΔIF vs time. (D) ΔIB vs time.

FIG. 12. (Color online) Sound stimuli for subject S. (A) The sound pressure spectrum level (L_p) for the sound used in the reflectance tests in the following air-pressure conditions: ambient, and pressurized responses at air pressures Ppt, TPP, and Pnt. (B) The absorbed sound power level (L_w) for the same sound presented under the same air-pressure conditions as in (A).

TEOAE mean signal levels did not differ from the TEOAE mean signal levels measured at ambient pressure in each ear canal. This finding was consistent with the fact that the mean TPP differed from ambient by only 2.7 daPa and served to demonstrate the feasibility of the pressurized TEOAE measurements.

TEOAE mean levels were reduced at frequencies between 0.7 and 2.8 kHz. Ear-canal pressurization effects on click and chirp TEOAEs were evident at larger pressure differences (−200, −100, 100, and 150 daPa) relative to ambient pressure. For a given pressure within the middle-ear cavity, a more positive tympanometric pressure in the ear canal pushes the tympanic membrane inwards and a more negative pressure pulls the tympanic membrane outwards. Such changes affect the quasi-static properties of the tympanic membrane, including its stiffness, and also affect the relative orientation of the ossicles that couple motions of the tympanic membrane to motions of the oval window of the inner ear.

The TEOAE level shifts at lower frequencies between 0.7 and 2 kHz in Figs. 2 and 6 showed a relative maximum close to 0 daPa (and thus also at the TPP). Such changes were relatively symmetrical with respect to positive and negative pressures, and were likely dominated by the pressure-induced mechanical changes on the tympanic membrane, i.e., increased middle-ear stiffness with increasing pressure difference across the tympanic membrane between the ear canal and middle-ear cavities. This finding replicates previous research described in Sec. I.

The pattern of TEOAE level shifts with pressurization was modified at higher frequencies (4, 5.7, and 8 kHz), as

the shifts were asymmetrical with respect to the polarity of the pressure change. Higher TEOAE mean levels were obtained at positive pressures (100 and 150 daPa) than at negative pressures (−100 and −200 daPa), although the change in mean level with pressure was non-monotonic. It is hypothesized that these are more controlled by changes in mechanical transmission through the ossicular chain. The TEOAE level changes at 2.8 kHz were intermediate between these extremal pressures, with more similarity to the changes at 2 kHz than those at 4 kHz.

The presence or absence of a detected TEOAE was assessed in each ear in terms of both SNR and CSM in the frequency and time domain. TEOAEs generated by both click and chirp stimuli were more often detected at frequencies between 2.8 and 8 kHz and times between 0.7 and 5.7 ms. These times were evaluated for the chirp stimulus condition in terms of the equivalent click representation of the TEOAE. This detection pattern was similar across pressurization conditions.

This project reported novel TEOAE measurements of GD, GS, IF, and IB under conditions of pressurization in the ear canal, and for TEOAEs generated using both clicks and chirps. The mean GD, GS, and IB of the click TEOAE responses were not affected by pressurization in the ear canal. In contrast, the mean IF was increased relative to the SEs between 2 and 2.8 ms at positive pressures (100 and 150 daPa) compared to the test conditions of negative pressure and TPP. The mean GD, IF, and IB of the chirp TEOAE responses were not affected by pressurization in the ear canal. In contrast, the mean GS of the chirp TEOAE was slightly decreased relative

FIG. 13. (Color online) TEOAE CSM (A) and SNR (B) are shown for subject S for the ambient test and pressurized test at the TPP under the following chirp stimulus conditions: power-weighted stimulus at TPP, incident pressure-weighted stimulus at TPP, power-weighted stimulus at ambient pressure, and incident pressure-weighted stimulus at ambient pressure. The dotted line in the CSM panel shows the critical CSM for detecting the TEOAE as present, and similarly for the SNR panel.

to the group SEs at 5.7 kHz at positive pressures compared to the test conditions of negative pressure and TPP. At 5.7 kHz, a reduced GS at positive pressures would be associated with a reduced tonotopic breadth of reflection sites contributing to the GD. These slightly different pressurization effects for chirp TEOAEs compared to click TEOAEs provide evidence of a difference in the nonlinear interactions on the basilar membrane. These interactions reveal a small asymmetry in the underlying cochlear mechanics elicited by the chirp stimuli that is not removed by inverse filtering the chirp TEOAE waveform to remove the phase characteristics of the chirp stimulus relative to the click stimulus (Keefe *et al.*, 2016). More research is needed to understand how ear-canal pressurization affects the transient dynamics of the cochlea that are generated by differing transients with similar power spectra and differing phase spectra.

Other studies have used the pressurized chirp TEOAE system described in the present work, although with less description of methodology. Putterman *et al.* (2017) found that TEOAEs recorded at ambient and TPP conditions performed equally in classifying ears as having normal hearing or a sensorineural hearing loss. The inclusion criteria for their study was based on ages between 18 and 89 yrs, normal otoscopy, normal 226 Hz tympanometry including a TPP within ± 100 daPa, and air-bone gaps of 10 dB or less between 0.5 and 4 kHz. Garinis *et al.* (2017) reported that TEOAEs recorded at ambient and TPP had a generally similar performance in classifying ears as having normal hearing or a sensorineural hearing loss in a group of cystic fibrosis patients who had received ototoxic drugs.

Results were described from a case study in an adult ear with ETD of reflectance and TEOAE tests recorded at ambient pressure in the ear canal and at varying tympanometric pressures. For the click stimulus used in the reflectance test, the pressure spectral density level L_p at the probe tip was similar for the ambient test, the test at a tympanometric positive tail pressure (Ppt of 200 daPa), and at a negative tail pressure (Pnt of -300 daPa). In contrast, L_p at the TPP of -165 daPa was reduced at frequencies up to 1.4 kHz and increased near 2.8 kHz.

Much larger differences across the pressure conditions were observed for the absorbed sound power spectral density level (L_w), with elevated L_w at TPP at frequencies from 0.25 to 2.8 kHz. That is, the ear was more efficient at absorbing sound power up to 2.8 kHz when tested at the TPP. The L_w was relatively similar for the pressure conditions of ambient and Pnt, but L_w was the smallest for the Ppt condition at frequencies between 1.4 and 2.8 kHz. This is because the positive Ppt increased the pressure difference across the tympanic membrane relative to the pressure close to the TPP of -165 daPa in the middle-ear cavities.

Using the chirp stimulus with constant incident pressure level across frequency, TEOAEs at TPP in the adult ear with ETD had increased SNR and CSM at frequencies from 0.7 to 2.8 kHz, and decreased SNR and CSM at 4 and 5.7 kHz. This transition near 3 kHz was similar to a previous test up to 5 kHz in a subject with a negative TPP (Marshall *et al.*, 1997). It was a similar transition frequency to the L_w measurement, which was larger in the test at TPP up to 2.8 kHz

than at ambient, and smaller at TPP from 4 to 8 kHz. There are insufficient data to parse this frequency effect into forward and reverse transmission components.

Using the chirp stimulus with constant incident sound power level across frequency, the TEOAE CSM and SNR were larger at TPP than ambient at all frequencies up to 4 kHz, and smaller at 8 kHz at which both CSM and SNR classified the TEOAE as absent across all pressure and stimulus conditions. Comparing the two TEOAE responses at TPP, the CSM and SNR were each larger for the stimulus calibrated to constant L_w across frequency compared to the stimulus calibrated to constant incident SPL for frequencies from 0.7 to 4 kHz. The latter was the highest frequency at which the mean TEOAE responses were classified as present in these two responses. This case study suggests a potential benefit to measuring TEOAEs at TPP using a stimulus calibrated to constant sound power level across frequency. Further measurements in groups of ears with conductive impairments are needed to evaluate whether this finding generalizes. The present finding supports the hypothesis that TEOAE measurement at TPP better reveals the presence of the cochlear generated signal by controlling for variations in middle-ear pressure that arise in some conductive-impaired ears.

Detailed calibration measurements were not performed for the sound sources and microphone over the range of excess air pressures between -200 and 150 daPa and test frequencies up to 8 kHz. The incident-pressure spectrum was measured at ambient pressure by inserting the probe into the long tube. Various measurements with the probe inserted into rigid-walled couplers showed much smaller shifts in SPL over the tympanometric range compared to the shifts in SPL observed with the probe inserted into the ear canal (e.g., see Fig. 1). As reported above, measurement-system distortion was absent in coupler recordings, which established a satisfactory level of transducer linearity. Thus, the dominant acoustic pressure shifts with changes in tympanometric air pressure measured in the ear recordings of sound stimuli, from which TEOAE responses were extracted and further analyzed using the TEOAE moments, were associated with the responses of the ear canal, middle ear, and cochlea, and were not due to a measurement-system artifact. It would be useful in future pressurized OAE research to calibrate over frequency at various excess air pressures over the tympanometric range, so that any air pressure-induced changes in microphone sensitivity magnitude and phase could be included in data analyses.

V. CONCLUDING REMARKS

This study demonstrated the feasibility of measuring TEOAEs at frequencies up to 8 kHz and at air pressures differing from ambient pressure using a TPP measured using a wideband reflectance tympanogram. In adults with normal hearing and TPPs close to ambient, the TEOAE data up to 2–2.8 kHz replicated previous studies in having reduced TEOAE levels at air pressures far removed from ambient pressure. A novel finding was the presence of an asymmetry in TEOAE levels at frequencies from 4 to 8 kHz, with slightly higher levels at positive air pressures in the ear canal. No change in TEOAE mean GD was observed across

pressure and stimulus conditions. Small differences were observed at positive air pressures in the ear canal for the mean IF of the click TEOAE at 2–2.8 ms and for the mean GS of the chirp TEOAE at 5.7 kHz. A case study in a single adult subject with ETD showed that TEOAE measurements at TPP improved the SNR and CSM at lower frequencies up to 2.8 to 4 kHz in an ear in which the TEOAEs were borderline at 5.7 kHz and absent at 8 kHz. The results of this case study suggest a possible benefit to calibrating the stimulus to constant absorbed SPL across frequency in TEOAE measurements, but further research is needed of pressurized TEOAEs in ears with middle-ear dysfunction.

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¹A preliminary account of these results were presented at the 2012 meeting of the Association for Research in Otolaryngology meeting by D. H. Keefe, L. L. Hunter, M. P. Feeney, D. K. Brown, and D. F. Fitzpatrick.

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