Characterizing spontaneous otoacoustic emissions across the human lifespan

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This study characterizes 1571 archival and newly acquired spontaneous otoacoustic emissions (SOAEs) from 632 human subjects with ages ranging from premature birth through the seventh decade of life. Automated detection and Lorentzian modeling were applied to identify SOAEs and characterize SOAE features throughout the human lifespan. Results confirm higher-level, higher-frequency, and more numerous SOAEs from neonates compared to young adults. Approximately 85% of newborns have measurable SOAEs as compared to 51%–68% for young adults. Newborn SOAEs are also an average of 5 to 6 dB higher in level than those from young-adult ears. These age differences may reflect immature ear-canal acoustics and/or the pristine condition of the neonatal cochlea. In addition, newborns as a group showed broader SOAE bandwidth and increased frequency jitter, possibly due to higher intracochlear noise; additionally, 22% of newborn SOAEs had a different, non-Lorentzian spectral shape. Aging effects were also observed: 40% of elderly ears had SOAEs, and these were greatly reduced in level, likely due to lower power gain in the aging cochlea. For all ages, SOAE bandwidths decreased with frequency in a way that mirrors the frequency dependence of stimulus-frequency otoacoustic emission delays as predicted by the standing-wave model of SOAE generation. © 2017 Acoustical Society of America.

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I. INTRODUCTION

Spontaneous otoacoustic emissions (SOAEs) provide a noninvasive window into the inner ear that can illuminate aspects of cochlear mechanics including power gain, frequency tuning, and delay. SOAE measurements made in human ears across the lifespan can probe the development, maturation, and aging of these features. Here, we study SOAEs over seven decades of life to explore changes in cochlear mechanics and SOAE generation as a function of age. Although previous studies have reported on developmental aspects of SOAEs (e.g., Burns *et al.*, 1992; Morlet *et al.*, 1993) and, minimally, on aging aspects (Kuroda, 2007), none have reported results over the wide range of ages investigated here. To facilitate comparisons across groups we adopt uniform SOAE measurement, detection, and analysis protocols. Motivated by previous efforts to automate the detection and modeling of SOAEs (e.g., Talmadge *et al.*, 1993; Zhang and Penner, 1998; Pasanen and McFadden, 2000; van Dijk *et al.*, 2011), we describe the refinement and extension of these strategies to improve the measurement of SOAE features in subjects from across the human lifespan.

II. METHODS

A. Subjects and groups

The 632 subjects participating in this project were divided into two groups. The Archival Group comprises 388

subjects for whom only SOAE spectra are available. The Archival data are particularly valuable because 320 of the records are from newborns; these data therefore allow us to characterize SOAEs at birth using a subject pool significantly larger than available in most early studies of neonatal SOAEs. Data from the Archival subjects were collected over a 10-yr period in the Abdala laboratory at either the House Ear Institute or the Infant Auditory Research Laboratory at the Los Angeles County + USC Women and Children's Hospital. In this group of historical data, SOAEs are preserved only in the form of fast Fourier transform (FFT) amplitude spectra computed at the time of measurement. In 58 of the Archival subjects, the spectra survived only in hard-copy form, with SOAE frequencies and levels notated on the page at the time of recording. The New Group comprises 244 mostly adult subjects in which 3-min ear-canal sound recordings were recently made and SOAEs measured as a prospective study. The sound files from these recordings were subsequently analyzed and manipulated offline in order to clean the data of noise, conduct fine-grained spectral analysis for identifying SOAEs, and model the results for quantifying SOAE features.

The Archival Group ($n=388$): We collected SOAEs from 206 premature newborns, 114 term newborns, and 68 adults (18–40 yr) who had participated in various hearing studies between 1996 and 2006. All adult SOAEs were recorded in a double-walled sound-attenuating booth (Industrial Acoustics) while the subject was comfortably seated in a reclining chair. Newborns were tested in either a hospital isolette or a specialized sound-attenuating isolette

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(Eckels ABC) while in a quiet room away from the nursery or in the NICU of Women and Children's LAC + USC Hospital. Either an ER10B+ or an ER10C probe microphone was used to record the ear-canal pressure; data collection and analysis were conducted using an Ariel 16+ DSP board or a 24-bit DSP DAQ with a custom-designed FFT spectrum analyzer. Microphone signals were high-pass filtered (700 Hz cutoff) and sampled at 50 kHz with a buffer length of 4096 samples; the resulting frequency resolution was ~ 12 Hz. Approximately 100 power spectra were averaged from 1 to 10 kHz for each ear and peaks at least 3 dB above the noise floor were identified as SOAEs. The noise floor was defined as the average of three points taken at the baseline on either side of an identified SOAE.

New Group ($n=244$): We collected SOAEs from 38 newborns (16 premature, 22 term), 8 6-month-old infants, 26 teens (13–17 yr), 74 young adults (18–25 yr), 36 middle-aged adults (40–58 yr), and 62 elderly adults (59–78 yr). A 180-s sound recording (24-bit, 44.1 kHz sampling rate) was obtained and high-pass filtered (300 Hz cutoff). Spectral analysis was conducted offline. Long duration (4-s) Hanning windows with 75% overlap were applied to reduce noise and achieve a frequency resolution of 0.25 Hz. An offline noise-rejection scheme was applied (see below). Squared FFT magnitudes were computed, averaged for non-rejected segments, and interpreted as power spectral density. The dB scale was normalized such that 0 dB corresponds to the power spectrum level of a signal at 0 dB re 20 μ Pa, analyzed in a 1-Hz bandwidth.

B. Noise rejection, peak-picking, and modeling

The techniques described in this section require ear-canal sound recordings and were therefore applied only to the New Group of data. To clean the recordings and remove potential artifacts, we rejected the noisiest 75% of the Hann-windowed time segments based on their root mean square (RMS) level; hence, only time segments with RMS levels in the lowest quartile contributed to the averaged spectra used for SOAE detection and analysis. This rejection strategy greatly reduced measurement noise related to subject movement or the acoustic environment, especially for frequencies below 2 kHz. With this technique, mean adult noise floor was roughly comparable to system noise; newborn noise was elevated compared to adult noise by 5–10 dB on average, but only at frequencies below 2 kHz (Fig. 1).

To identify potential SOAEs in the averaged spectrum we applied a criterion based on the standard deviation (SD) of the local noise floor. We estimated the local noise baseline at each frequency using a Hampel identifier to smooth the spectrum over a 300 Hz range (i.e., 150 Hz on either side of every point across the frequency range) and took the median of the smoothed segment as the local noise baseline (Hampel, 1974). SDs were calculated as 1.483 times the median absolute deviation (MAD) of the noise about this baseline. The Hampel method is considered a robust means of calculating data trends in the presence of outliers—in this case, the outliers are the SOAE themselves (Liu *et al.*, 2004).

FIG. 1. The mean noise baseline achieved after data cleaning in each of four age groups from the New Group. System noise (measured by inserting the probe in a Bruel and Kjaer 4157 ear simulator and averaging in the absence of stimuli) is shown for comparison. The adult groups track the system noise within a few dB over the entire frequency range. The newborns show noise elevated by 5–10 dB below 2 kHz, but adult-like noise levels above this frequency.

The identification of the “true” SOAEs from among the many peaks in the spectrum proceeded in two stages. The initial peak-picking stage was liberal and identified all spectral peaks with heights at least 2 SD above the local noise baseline. To eliminate narrow spectral artifacts, we required that the peak satisfy the 2-SD criterion over a span of at least nine consecutive points, ensuring a minimum bandwidth of 2.25 Hz. Additionally, candidate SOAEs had to be at least 30 Hz apart; if more than one peak was identified in any 30 Hz segment, only the highest peak was taken. The 30-Hz criterion, which represents 0.1 octave at 433 Hz and a smaller fraction of an octave at higher frequencies, was chosen based on the expected minimum SOAE spacing reported in previous work (Zwicker, 1990; Talmadge *et al.*, 1993; Shera, 2003).

A second stage of modeling and peak-picking was initiated on all peaks satisfying the initial 9-point bandwidth criterion. Candidate SOAEs were fit to a Lorentzian model to quantify features of interest, including their amplitudes and bandwidths. The Lorentzian model is widely used to characterize the frequency response of forced harmonic oscillators. Previous studies have applied Lorentzian modeling to SOAEs for automatic detection (Talmadge *et al.*, 1993; Pasanen and McFadden, 2000; Van Dijk *et al.*, 2011) but only in young-adult ears and mostly to explore methodology. In the present study, we applied the Lorentzian model to SOAEs for the purpose of studying how SOAE features change across the human lifespan and to provide some refinements in methodology.

Prior to fitting the spectrum, the Lorentzian was converted to the dB scale:

$$S(f) = 10 \log_{10} \left(\frac{S_0}{1 + 4 \left(\frac{f - f_0}{\Delta f} \right)^2} + N \right),$$

where S_0 is the peak height, f_0 the center frequency of the SOAE, Δf the bandwidth of the SOAE at half-power (aka full width at half-maximum), and N is the noise floor (assumed constant over the fitting bandwidth). The Lorentzian model was fit to the spectrum (in dB) over a frequency interval centered on the candidate peak. The interval was taken as 0.1 octave for candidate SOAE frequencies less than 2.9 kHz and a constant 200 Hz at higher frequencies. From values of the model parameters we can calculate the peak level as $10 \log_{10}(S_0 + N)$ (in dB re 20 μ Pa) and SNR as $10 \log_{10}(1 + S_0/N)$ (in dB). Additionally, one can estimate the SOAE sound (power) level which corresponds to the area enclosed by the peak as: $S_0 \pi \text{BW}/2$ and the total dB sound pressure level (SPL) as $10 \log_{10}(S_0 \pi \text{BW}/2)$ (in dB SPL). A goodness-of-fit measure was defined as the RMS dB difference between model and data over a 35 Hz region centered at the peak (i.e., 141 points). At the modeling stage, only spectral peaks with peak heights at least 5 SD above the baseline noise were accepted as true SOAEs for further analysis.

Talman and colleagues (1993) suggest that parameters of the Lorentzian model can be well determined if the half-power bandwidth of the SOAE is at least four times the frequency resolution of the spectrum. van Dijk *et al.* (2011) suggest choosing the spectral resolution of the analysis so that each peak includes at least 10 points for modeling. Here, we used an analysis resolution of 0.25 Hz, which requires an SOAE half-power bandwidth of 1 Hz according to the Talman *et al.* criteria; most (78%) of our 576 peaks met this requirement. All of our 576 peaks include at least 10 points above the noise (by the 2 SD criterion), as suggested by van Dijk and colleagues.

C. Analyses

Descriptive statistics were conducted separately for the Archival and New Groups to quantify central tendencies in SOAE prevalence, number of SOAEs per ear, and SOAE level and frequency. Additionally, for the 244 subjects in the

New Group, modeling the SOAEs provided estimates of SOAE level, SNR, and bandwidth.

The spacing between adjacent SOAE peaks was also calculated for each age group. In order to increase the number of SOAE pairs available for spacing analysis, SOAE detection criteria were relaxed and defined as spikes 2 SD (vs 5 SD) above the noise baseline. As a reference, this change in criteria added 13 additional SOAEs to the teen and young-adult group. The fractional spacing metric was defined as the frequency difference between two neighboring peaks divided by their geometric mean. SOAE spacing was analyzed as a function of age.

III. RESULTS

A total of 995 SOAEs were identified in the 388 subjects of the Archival Group, which consists mostly of newborns. A total of 576 SOAEs were identified in the 244 subjects of the New Group, which consists mostly of adults.

A. Archival SOAE recordings

1. Group statistics

We categorized the Archival SOAEs into three age groups: premature newborns, term newborns, and adults. Premature newborns account for 67% of the SOAEs in this group; term infants account for 32%, and adults for only 1%. Example spectra are shown in Fig. 2 for newborns. 84% of premature and 80% of term newborns have at least one SOAE; together, premature and term newborns have an average of 3.6 SOAEs per emitting ear. The mean SOAE levels are indistinguishable between newborn groups and when combined, average 11.3 dB SPL (SD = 6.1 dB).¹ The mean SOAE frequency for newborns is 4445 Hz; individual SOAE frequencies range from 1000 to 9800 Hz. Of the adults, 51% have at least one SOAE, and show an average of 1.9 SOAEs per emitting ear. Mean adult SOAE levels are 4.2 dB SPL, considerably lower than that observed in newborns. The mean frequency, 2832 Hz, is also lower than newborn

FIG. 2. Example spectra and SOAEs from newborns in the Archival group. The inset shows the spectrum from a premature newborn with the highest level SOAE we have recorded, 36 dB SPL. No other age group showed SOAEs of this magnitude. In general, these exemplars illustrate the SOAE trends in the Archival data set, i.e., more numerous and higher level SOAEs in newborns than adults.

SOAEs. The inset in Fig. 2 presents data from a premature newborn with an unusually high-level SOAE. These so-called “super-emitters” (>30 dB SPL SOAE) were rare but only ever observed in the premature group.

Figures 3(A) and 3(B) show SOAE frequency and level histograms for the 388 subjects in the Archival Group. Because the number of observations varies greatly among groups, we show the percentage of SOAEs falling into each level and frequency bin, rather than the absolute count. Frequency was binned into 1/3 octave intervals and level into 2 dB bins. Figure 3(A) clearly illustrates the trend for higher frequency SOAEs in newborns. Age effects in SOAE level are less clear; as noted in Fig. 3(B), however, age differences are evident in the tail of the distribution, which is skewed toward higher levels in newborns: 36% of newborn SOAEs have levels greater than 10 dB SPL. In the adults, only 6.7% of the SOAEs are above 10 dB SPL. Figure 3(C) displays SOAE level vs frequency for every measured SOAE. The age groups are distinguished by symbol.

There appear to be no clear developmental trends within the newborn group. Three sub-groups of prematurely born neonates are available for comparison: 31–33 weeks post-conceptual age (PCA), 34–36 weeks PCA, and 37–40 weeks PCA. As the prematurely born neonates increase in age and approach term-like status (40 weeks), their SOAEs increase slightly in level, averaging a 1 dB change. However, variability within each sub-group is greater than the between-group differences ($SD = 6$ dB). Past work has suggested that SOAEs shift slightly toward higher frequencies as premature newborns mature (Brienesse *et al.*, 1997; Brienesse *et al.*, 1998), but we see no clear evidence for this trend in our data. Although mean SOAE frequencies jump several hundred Hz upward (329 Hz) between the youngest (31–33 weeks PCA) and the intermediate (34–36 weeks PCA) premature newborn groups, this effect disappears by term-like age (37–40 weeks PCA), and the variability within age sub-groups is several times larger than the group mean differences.

We find sex and ear trends on SOAEs similar to those previously reported. Since these are not novel findings, we report only mean values to confirm and reinforce previously

documented results. Adult females have a higher prevalence of SOAEs than adult males (65% vs 36%) and their mean SOAE levels are 1.5–2 dB higher than those observed in male ears. Similarly, newborn females have a higher prevalence of SOAEs, more SOAEs per emitting ear, and slightly higher SOAE levels than newborn males. In newborns, right ears produce slightly higher SOAEs (by 1 dB on average) than left ears; no similar trend is noted in this small group of adults. However, both adults and newborns show more SOAEs in the right ear. Overall, the trends previously reported in the literature about the effects of ear and sex on SOAEs are upheld in our large database and appear to hold in both adult and newborn subjects.

B. New SOAE recordings

1. Group statistics

We categorized SOAEs from the New Group into seven subgroups for display purposes (see Fig. 4 for example spectra) but combined term and prematurely born neonates, as well as teens and young adults for analysis because their trends and mean values were indistinguishable. (We also observed similarity of results between term and prematurely born neonates in the Archival Group.) Hence, we conducted statistical analyses for four age groups: newborns, teen/young adults, middle-aged adults, and elderly adults. (For some figures, we combine middle-aged and elderly adults as noted.) Although we identified spectral peaks as SOAEs based on a criterion SD from the baseline noise, the following associations allow the reader to link SDs to the more familiar dB SNR metric often used to identify SOAEs: 5 SD in the young-adult group is comparable to a mean SNR of 2.8 dB at the highest frequencies and 3.6 dB at the lowest; in newborns, 5 SD is equivalent to 3–5 dB SNR across frequency; and in older individuals, to 3–4 dB SNR across frequency.

In the newborn group, 84% of ears have at least one SOAE and average 4.5 SOAEs per emitting ear ($SD = 3.5$); the mean SOAE level is 9 dB SPL.² The mean SOAE frequency in newborns is 3000 Hz, lower than previously reported. We suspect that the sensitive peak-picking and the

FIG. 3. (Color online) Panels (A) and (B) show histograms of SOAE frequency and level for the Archival Group. Counts are shown as a percentage of the total number of SOAEs in each age group because of the varying numbers of subjects in each. Panel (C) shows a scatterplot of every SOAE in the Archival Group plotted as level vs frequency. Most notable is the higher level SOAEs from newborns.

FIG. 4. Example SOAE spectra from individual ears representing each of the seven age categories in the New Group: newborns (premature and term), 6-month-old infants, teens (13–17 yr), young adults (18–25 yr), middle-aged adults (40–58 yr), and elderly adults (59–78 yr). The thick gray line in each panel is the median noise baseline value and the thin black line above the noise denotes the 5 SD boundary for this particular ear. Peaks marked with a circle were identified as true SOAEs; peaks marked with an x are those with insufficient SNR; unmarked peaks are too narrow to meet the nine-consecutive-points criterion. Also shown is an inset of an atypical elderly subject with many more SOAEs (>2 SD from the mean) than typical for that group.

noise-reduction strategies applied here enable the identification of SOAEs at lower frequencies and SNRs than in the past, pushing the mean frequency lower.

In the combined group of teens and young adults, 68% of ears have at least one SOAE and they average 3.8 (SD = 2.6) SOAEs per emitting ear. Mean SOAE level in this group is ~4 dB SPL and the mean frequency is 2400 Hz.

In the middle-aged group, 58% of ears have at least one SOAE and average 3.8 SOAEs per emitting ear (SD = 2.9), similar to their young-adult counterparts. In the elderly group, 40% of ears have SOAEs and an average of 2.4 SOAEs per emitting ear (SD = 1.8). Mean SOAE levels for the combined middle/elderly group range from -1.9 to -2.5 dB SPL, and the mean SOAE frequency for this group is 2700 Hz. We note that 20% of the elderly group show more numerous SOAEs per ear than expected from a normal distribution. In this 20% sub-group of elderly subjects, the number of SOAEs per ear (5–6 SOAEs per ear) is more than

2 SD from the group mean. Figure 4 inset shows one such elderly ear. To present a more comprehensive view of SOAEs beyond central tendencies, Figs. 5(A)–5(C) display SOAE frequency and level histograms for the four age subgroups and a scatterplot of SOAE level vs frequency for all identified SOAEs.

Clearly, the prevalence, number of SOAEs per ear, and SOAE level all decrease with age between the newborn period and senescence. We hypothesized that these collective trends might be explained by one general age effect: the general reduction of SOAE level with age and the associated reductions in SNR, which subsequently affect all of the other metrics. Cochlear gain is thought to determine or stabilize the amplitude of the SOAE, and as cochlear gain decreases with age, so does the SOAE peak level, making the emissions more difficult to reliably detect with a fixed noise level. With age, some SOAEs may disappear completely, or sink into the noise floor and become unmeasurable. To explore

FIG. 5. (Color online) Panels (A) and (B) show histograms of SOAE frequency and level for the New Group. Counts are shown as a percentage of the total number of SOAEs in each age group because of the varying numbers of subjects in each. Panel (C) shows a scatterplot of every SOAE in the New Group plotted as level vs frequency. The newborns show the largest percentage of SOAEs at high frequencies and also the highest-level SOAEs in any age group.

this hypothesis, we calculated the rate at which mean SOAE SNR decreases with age, which we found to be 0.6 dB per decade. We plotted SOAE signal-to-noise histograms for the four subgroups (not shown) and then shifted the newborn histogram by 0.6 dB per decade, in an attempt to match the mean age of each of the other groups. The shifted newborn SOAE SNR histograms matched the histograms of the older age groups relatively well, at least in their overall configuration. This finding suggests that the observed SOAE aging trends may be driven primarily by a loss of cochlear gain, which reduces SOAE level and associated SNR, thereby affecting all other SOAE measures.

2. SOAE model fits

Figures 6(A)–6(F) illustrate the results of fitting the Lorentzian model to SOAEs from a single adult ear. Examples of high-level, intermediate, and low-level SOAEs are shown. Model curves with RMS residuals less than ~ 2 dB generally provide visually satisfactory fits to the data. Although the RMS residuals are greater than 2 dB for only 3.5% of young-adult SOAEs, the residuals exceed this value in 22% of newborn SOAEs. Thus, although the Lorentzian model provides a good fit for nearly all of the adult SOAEs, the model is less successful for newborns.

Figures 7(A)–7(D) provide four example newborn SOAEs with poor model fits. A typical model-data deviation noted for newborn SOAEs (but never for adults) is an abrupt vertical departure from baseline (vs the more gradual adult SOAE “skirt”). Compared to the best-fit Lorentzian model, the neonatal SOAEs producing poor fits are broader at the peak and narrower at the base, almost “rectangular” in shape, manifesting a narrower skirt region near baseline and a broader width at half-power, where the model bandwidth parameter is determined. Sometimes data appear more scattered near the peak of the SOAE [e.g., panel (C)], but in all cases the noise floor is low and stable and cannot easily account for the relatively poor fits. Although we find no adult SOAE with these spectral features, they occur in both

term and premature newborns and for both low and high-frequency as well as low- and high-level SOAEs.

3. SOAE bandwidth

Although the best-fit model estimated parameters such as SOAE frequency and peak height well in newborns, it sometimes underestimated the bandwidth, BW. We therefore developed an alternative, model-independent measure of bandwidth based on the area under the SOAE peak. We define the Lorentzian-equivalent BW as $BW_{LE} = 2ERB/\pi$, where ERB is the so-called equivalent rectangular bandwidth of the SOAE. The ERB is found by regarding the SOAE spectrum as a filter and computing the bandwidth of the rectangular filter with the same peak height that passes the same total (integrated) power. The factor of $2/\pi$ ensures that BW_{LE} equals BW when the spectrum is truly Lorentzian. Thus, BW_{LE} provides an accurate measure of bandwidth that can be computed for all SOAEs but reduces to the Lorentzian value BW when the model fits well. Figure 8 plots the ratio BW/BW_{LE} as a function of SOAE level. The ratio is generally close to one for SOAEs of low and moderate levels—that is, for the majority of SOAEs—but decreases at higher levels, indicating that the Lorentzian model systematically underestimates the bandwidths of high-level SOAEs. Only BW_{LE} is used as a metric of SOAE bandwidth in analyses.

Figure 9 plots fractional SOAE bandwidths, BW_{LE}/f_0 , as a function of SOAE level such that higher values on the y-axis indicate broader bandwidths. Symbols denote individual SOAEs in each age group while loess trend lines and their 95% confidence intervals guide the eye. For all ages, SOAE bandwidths decrease as SOAE levels increase. This trend was reported previously in adult ears (Talmadge *et al.*, 1993; van Dijk *et al.*, 2011), and here we confirm the same pattern in newborns. Two-way ANOVAs exploring the effect of age, frequency, and level on fractional bandwidth find a significant effect of SOAE level and frequency ($F = 34$; $p < 0.0001$; $F = 13.77$; $p < 0.0001$): the taller the SOAE peak or the higher its frequency, the smaller its

FIG. 6. (Color online) Six SOAEs from one young-adult ear and their Lorentzian model best fits. Parameters for each fit are given. Note that the goodness-of-fit as shown by the RMS residual did not depend heavily on SOAE level or frequency in these examples although in general, the model underestimated the BW of higher-level SOAEs. Generally, when the SOAE level was high, the bandwidth (BW/f_0) was narrow. Also, note that the lower the noise floor, the smaller the required standard deviation to consider an SOAE present.

fractional bandwidth. The analysis of variance (ANOVA) also found an effect of age on SOAE bandwidth ($F = 7.7$; $p < 0.0005$; no interaction). Newborns have larger SOAE fractional bandwidths than adults irrespective of level or frequency. Paired age contrasts (using a Bonferroni correction) confirmed newborn SOAE bandwidths to be broader than SOAEs from both the teen/young adult group ($p = 0.0013$) and the middle-aged/older adult group ($p = 0.0012$). No systematic differences in SOAE fractional bandwidths are noted between young-adults and middle-aged/older adult groups. The relatively broad bandwidths of newborn SOAEs are particularly noteworthy given that newborns also exhibit higher-level and higher-frequency SOAEs, both of which would tend to bias their SOAEs toward narrower bandwidths.

4. SOAE frequency jitter

To explore time-domain correlates of the broader bandwidths seen in newborns, we assessed short-term SOAE frequency stability (frequency jitter) in a subset of adult and neonatal subjects. We defined the jitter as the range of frequencies over which an SOAE varied during the 3-min

recording. To find this range, we divided the 180 s of ear-canal recording into 180 non-overlapping, 1-s segments; performed an FFT on each segment (Hann window, 1 Hz resolution); identified the location of the spectral maximum within a $\pm 3\%$ range around the nominal (i.e., previously identified) SOAE frequency; and constructed a histogram of the resulting peak frequencies (1 Hz bin width). Only spectral peaks at least 5 SD above the noise baseline computed for their respective 1-s segment are included. Two example histograms are shown in Fig. 10. We defined the jitter bandwidth BW_{JIT} as the inter-quartile range of the distribution around the nominal SOAE frequency peak. This range, when divided by the SOAE frequency (and multiplied by 100), provides a percent frequency jitter index for each SOAE. Like BW_{LE} , the jitter bandwidth BW_{JIT} has the advantage of being independent of the Lorentzian model and thus provides a measure uninfluenced by any goodness-of-fit differences among age groups.

We computed BW_{JIT} for a representative sample of ears from each group, ranging from 25% to 50% of the total data. In the process, we eliminated nine SOAEs from newborns and one SOAE from an elderly ear whose histograms were essentially flat, showing no clear maximum around the

FIG. 7. (Color online) Four newborn SOAEs and their Lorentzian model best fits. Comparisons between adult fits in Fig. 6 and newborn fits here show that the Lorentzian model sometimes fails to capture the shape of the newborn SOAE. Mismatches are especially evident in the skirt region and in the underestimation of emission bandwidth near the peak. Model RMS residuals exceeded 2 dB in 22% of newborns but in only 3.5% of young-adult Lorentzian-model fits.

nominal SOAE frequency. All four age groups show mean SOAE frequency jitter of less than 1%. Past work has also reported remarkable frequency stability of SOAEs in newborns (Burns *et al.*, 1994). A frequency $\times$ age ANOVA on the frequency jitter metric finds a significant effect of age ($F = 7.28$; $p = 0.0008$) but no effect of frequency: newborns have a percent frequency jitter that is three times that of teen/young adults, consistent with the broader SOAE bandwidth estimates. Middle-aged/elderly adult subjects also have slightly increased frequency jitter compared to teen/young-adults. Paired contrasts show newborns to have

significantly greater jitter than young adults ($p = 0.001$), while the middle aged/elderly group have borderline greater jitter than the teen/young-adult group ($p = 0.02$). There appears to be no significant difference in SOAE frequency jitter between newborns and middle-aged/elderly adults.

Figure 11 shows a scatterplot of BW_{LE}/f_0 vs BW_{JIT}/f_0 along with loess trend lines for each age group superimposed on the data. A line of unity slope approximates the relationship over most of the range, indicating an approximate equality between frequency jitter and SOAE bandwidth. At the largest jitters the trend deviates from the linear relationship and BW_{JIT} overestimates BW_{LE} .

FIG. 8. (Color online) Scatterplot showing values of the ratio BW/BW_{LE} vs SOAE level. Age groups are identified by symbols. A loess trend line to the pooled data is shown to guide the eye. Close to one for the majority of SOAEs at low and moderate levels, the ratio decreases at higher levels, indicating that the Lorentzian model systematically underestimates the bandwidths of high-level SOAEs.

FIG. 9. (Color online) Scatterplot showing SOAE fractional bandwidths BW_{LE}/f_0 vs SOAE level. Age groups are identified by symbols. Loess trend lines and 95% confidence intervals for each group are shown for age comparisons. SOAE bandwidths in newborns are significantly broader than bandwidths from the other two age groups.

FIG. 10. Two example histograms used to determine SOAE jitter bandwidth BW_{JIT} . The histograms summarize the results of spectral analysis performed on each of the 180 1-s segments of the 3-min ear-canal recording. Counts give the number of times each frequency bin along the abscissa locates the Fourier coefficient of maximal amplitude about the nominal SOAE frequency. Counts do not necessarily sum to 180 because a 5 SD criterion was applied to the spectral peak of each 1-s segment in order to reduce noise. The jitter bandwidth BW_{JIT} is the interquartile range (IQR) of the histogram. The histograms shown here are from adult SOAEs.

5. SOAE spacing

We quantified the frequency spacing of neighboring SOAEs (at frequencies denoted f_a and f_b) using the dimensionless ratio N_{SOAE} , defined as $\sqrt{f_b f_a} / (f_b - f_a)$ with $f_a < f_b$; thus, N_{SOAE} is the geometric mean of the SOAE frequencies divided by their difference.³ Figure 12 shows a scatterplot of SOAE spacing N_{SOAE} values across frequency. Each symbol represents an adjacent pair of SOAEs from the same ear. Closely spaced SOAE pairs appear near the top of the plot; more widely spaced emissions appear near the bottom. The solid line represents the N_{SOAE} trend for the characteristic minimum spacing from Shera (2003). Small values of N_{SOAE} far from the trend line are due to pairs of adjacent SOAEs spaced at intervals much greater than the characteristic minimum spacing. Wide spacings can occur for many reasons, including the existence of SOAEs that are simply too weak to be reliably detected. The minimum spacing for newborn and young adult SOAEs appears similar to the reported trend, as shown by the triangle and circles that cluster near the line across the frequency range. However, SOAE spacing measured from older individuals (filled squares) roughly cluster near the trend line only at frequencies below 2 kHz.

FIG. 11. (Color online) Scatterplot of BW_{LE}/f_0 vs BW_{JIT}/f_0 showing the relationship between the Lorentzian-equivalent and jitter bandwidths. Age groups are identified by symbols. Loess trend lines for each age group are superposed on the data. A line of unit slope (dashed line) approximates the relationship over most of the range.

At higher frequencies, the minimum SOAE spacings from the elderly group are larger, and N_{SOAE} falls below the published trend.

IV. DISCUSSION

Using a large group of 1571 SOAEs from 632 ears, we explored how SOAEs change across the human lifespan. To identify SOAEs and quantify their features we implemented an automated SOAE detection and analysis program that includes rigorous noise-rejection and modeling. Several research groups have previously developed automated algorithms to identify SOAEs in human ears, and some of these also employ the Lorentzian model to characterize SOAE features (Talmadge *et al.*, 1993; Pasanen and McFadden, 2000; van Dijk *et al.*, 2011). We extended and improved previous algorithms by enhancing the frequency resolution of the analysis and employing a Hampel smoothing technique to estimate the noise baseline (and hence, the SNR of the SOAE). Use of the Lorentzian-equivalent bandwidth also enabled us to obtain reliable, model-independent estimates of bandwidth. In addition, our work extends these studies by employing a large group (244 ears) of subjects ranging from prematurely born neonates to subjects in their seventh decade of life in order to characterize SOAE features throughout the human lifespan.

Our prevalence figures for young adults are not unlike those reported in the aforementioned studies testing automatic-detection algorithms; we find that nearly 70% of young-adult/teen ears have SOAEs. Prevalence figures of 72%–75% were reported in the modeling studies cited above (with the exception of the study with $n = 8$ from which no prevalence figure could be estimated). We found an average of 3.8 SOAEs per young-adult ear, which falls between two studies with comparable peak-picking and modeling criteria (3.6–4.7). The earliest study by Talmadge and colleagues found many more SOAEs per ear, averaging nearly seven;

FIG. 12. (Color online) Scatterplot of values N_{SOAE} vs SOAE frequency. N_{SOAE} is defined as $\sqrt{f_b f_a} / (f_b - f_a)$ and represents the inverse fractional spacing between adjacent SOAEs. Age groups are identified by symbols. The solid line represents the power-law approximation $(13.7(f/\text{kHz})^{0.31})$ to the peak of the distribution (characteristic minimum spacings) reproduced from Fig. 3 of [Shera \(2003\)](#).

however, their criteria for SOAE detection were more liberal (2 SD) and their SOAE identification criteria required only five consecutive points whereas we require nine points at least 5 SD above the noise baseline. In general, the sparse group statistics provided in these mostly methodological papers agree with our numbers for the young-adult group.

Our results from two groups of subjects—Archival and New—generally confirm earlier findings of how SOAEs change during development: Newborns have larger SOAEs, more prevalent SOAEs, and more SOAEs per emitting ear than do young adults. Additionally, we extended the study of SOAEs into senescence, finding that SOAEs become weaker, less prevalent, and less numerous per emitting ear in the seventh and eighth decades of life. Despite these aging effects, 20% of the elderly ears tested show unexpectedly robust generation of SOAEs. Notably, we find that a significant subset of newborn SOAEs are differently shaped than adult SOAEs and broader in bandwidth, likely associated with increased frequency jitter.

A. Development and aging of SOAEs

Although some of the early SOAE studies found no difference in SOAE prevalence between newborn and adult ears ([Strickland et al., 1985](#); [Burns et al., 1992](#)), later reports ([Kok et al., 1993](#); [Morlet et al., 1995](#); [Abdala, 1996](#)) and the current study do find a higher prevalence in newborns. The early work may not have had the advantage of high-quality signal processing, and their spectral resolution was not nearly as fine as that employed here. Our combined group statistics (Archival and New) suggest that $\sim 85\%$ of newborns have at least one SOAE, although on average they show 4–5 SOAEs per emitting ear. This stands in contrast to adult estimates that between 51%–70% show at least one spontaneous emission (the lower end of this prevalence estimate, 51%, was taken from our own archival studies

analyzed with relatively poor frequency resolution, 12 Hz). The present study of 1571 SOAEs establishes that newborn SOAEs have higher mean levels than SOAEs in adults, are centered at higher frequencies, and are more numerous per ear. Our large data set combined with effective noise-reduction, objective SOAE detection, and parametric modeling make this a reliable estimate of SOAE prevalence and strong evidence for a maturational effect on SOAEs.

The source of this developmental difference in SOAE prevalence is unclear. Increased prevalence in newborns has been hypothesized to result from the smaller volume and diameter of the newborn ear canal, which acts to augment emission pressure levels at most frequencies, enhancing their detection for a fixed noise level (see [Abdala and Keefe, 2012](#)). However, this explanation would need to account for a prevalence difference of nearly 20%–30% between newborns and adults and mean SOAE level differences of 5–6 dB. Furthermore, newborns have elevated noise floors relative to adults, which could counter the signal boost due to smaller ear-canal volume. Another possibility is that the pristine newborn ear has a fuller complement of sensory cells and a more robust cochlear amplifier with larger gain compared to adults, who have had more prolonged exposure to noise and ototoxins. Indeed, the gerbil cochlear amplifier shows a transient period of overshoot for cochlear gain during neonatal life ([Mills and Rubel, 1996](#)). A similar overshoot has been proposed for human newborns ([Abdala and Keefe, 2012](#)). Whether the root cause is conductive or cochlear in origin—or a combination of the two—there is a clear developmental effect on SOAEs, suggesting immaturities in the human auditory system at birth. These findings are consistent with other reports of robust cochlear reflection from newborns, including a high-amplitude reflection component of the DPOAE ([Abdala and Dhar, 2010, 2012](#)) and stimulus-frequency OAEs that are larger than in adults ([Kalluri and Abdala, 2015](#)).

We also found aging effects on SOAEs and suspect that many of these effects can be understood as a consequence of the age-related loss of cochlear amplifier gain. According to the standing-wave theory of SOAE generation (e.g., [Shera 2003](#); [Ku et al., 2009](#)), decreased gain predicts a reduction in SOAE prevalence, number per ear, and level, as observed in the present study. Previous studies ([Abdala and Dhar, 2012](#); [Dewey and Dhar, 2016](#)) have hypothesized that the aging cochlea becomes more mechanically irregular (e.g., due to scattered damage or loss of outer hair cells), augmenting the reflection of traveling waves. In our sample of elderly subjects, 20% show an unexpected result: The number of SOAEs per ear (5–6) is more than 2 SD above the group mean. In contrast, only 5% of teens/adults showed this same outlier tendency. It appears that the distribution of SOAEs per emitting ear is skewed toward higher values in the elderly. This finding is consistent with the idea that a subgroup of aging ears may have robust cochlear reflection despite their age, and this reflection could be related to increased irregularity in the cochlea (combined with relatively intact cochlear tuning). How aging ears that show strong reflection are different from those that show a more

predictable weakening of cochlear reflection and SOAEs remains unclear.

B. SOAE bandwidths, frequency jitter, and model fits

Our results indicate that SOAE bandwidths are broader in newborns than in all other age groups. Broader newborn SOAEs could be the result of the increased measurement noise in these subjects. Higher noise floors could produce more instability and variability in the peak measurement, and this could manifest as increased bandwidth. However, this hypothesis predicts that age differences in SOAE bandwidth should be most prominent below 2 kHz, where newborn noise is elevated (see Fig. 1) yet our statistical analysis of SOAE bandwidth finds no interaction between age and frequency. Evidently, the age difference in SOAE bandwidth is not restricted to the low-frequency range. Neither are the broader SOAEs easily explainable by a reduced SNR (separation between SOAE peak and noise) in the neonatal population, since mean SOAE SNR values are comparable in newborns and adults (~ 15 dB overall). Furthermore, the age effect on SOAE bandwidth persists when it is considered as a function of SNR (rather than of absolute SOAE level, as shown in Fig. 9); newborns show broader SOAEs than the other ages even when SNR is equivalent among groups. SOAEs with broader bandwidths appear to be an intrinsic characteristic of newborn SOAEs.

As a correlate of their broader bandwidths, newborn SOAEs manifest greater frequency jitter over time. When the measured frequency of a given SOAE shifts about from one second to the next, the long-term averaged spectrum encompassing all these individual frequencies will necessarily be broader. Our results indicate that the bandwidth of the SOAE is indeed related to the SOAE frequency jitter; in all age groups, the two indices are nearly equal over most of the range of measured bandwidths. Although the fractional frequency jitter is below 1% for all ages, those with the most unstable frequency peaks (newborns) also have the broadest SOAE bandwidths. We cannot prove that increased frequency instability of the sort quantified by BW_{JT} is the only contributor to the broader SOAE bandwidths seen in some newborn SOAEs, nevertheless, the measures are closely associated.

The broader bandwidths and unusual spectral shapes of some newborn SOAEs are also manifest in their poorer fit to the Lorentzian model. Because our noise-rejection algorithms rendered the average SNR comparable across age groups, it seems unlikely that noise levels measured in the ear canal can explain this age difference in the success of the Lorentzian model. Although the mean noise floor measured in the ear canal is only elevated in newborns for frequencies below 2 kHz, most of the newborn fits with poor RMS residuals are at frequencies above 2 kHz (26/32 fits). Thus, more than 80% of the poor newborn model fits are at frequencies where the ear-canal noise floor is essentially equivalent across age groups. Since almost a quarter of newborn SOAEs are not well fit by the Lorentzian model, a sizable subset of newborn SOAEs appears to have fundamentally

different shape (i.e., spectral content) than that observed in adult ears.

The source of this developmental effect on SOAE shape and bandwidth is less clear. SOAEs may be different in newborns due to immature boundary conditions in the cochlea. The global standing-wave model posits that SOAEs depend in part upon the reflection of outgoing energy at the stapes, creating a cascade of multiple internal reflections within the cochlea. Because newborns have a stiffer middle ear, stapes reflection may be more robust in this age group (Dhar and Abdala, 2007; Abdala and Dhar, 2010, 2012), perhaps contributing to their more numerous and higher-level SOAEs. Along similar lines, the standing-wave model suggests that temporal fluctuations in middle-ear impedance (and hence, stapes reflectance) can broaden SOAE bandwidths. Such fluctuations may arise, for example, from efferent feedback or from the spontaneous contraction of the middle-ear muscles. If these fluctuations are stronger in newborns, then the model would predict increased frequency jitter and broader SOAE bandwidths in this group.

Intracochlear noise sources can also broaden SOAE bandwidths. One potential source is the neonatal heartbeat, which is considerably faster than the adult heartbeat and potentially more intrusive given the smaller size of the neonatal torso and the resulting proximity of the heart to the ear in newborns. Long and Talmadge (1997) observed regular sidebands when recording SOAEs with high frequency resolution in adults. Interestingly, the periodicity of these sidebands was correlated with heartbeat, which was monitored in each subject. This result suggests that the heartbeat produced a frequency modulation of the SOAE, which could impact its measured bandwidth by producing frequency jitter. Long and Talmadge speculate that a change in the mass of the organ of Corti due to fluctuating blood flow through the basilar membrane vessel might be responsible for modulating SOAE spectral characteristics and hence producing the observed sidebands. They did not test newborn ears but it is plausible that the heartbeat and associated blood flow through the neonatal cochlea might have even more of an impact on the newborn SOAE. Because we did not monitor heartbeat, and did not analyze SOAEs with sufficient resolution to resolve sidebands, we cannot directly address this hypothesis.⁴

C. SOAE spacing

The characteristic minimum spacing between SOAEs provides another feature of interest for understanding the mechanisms underlying SOAE generation and their possible variation across the human lifespan. Below 2 kHz, minimum SOAE spacings quantified as N_{SOAE} cluster around the trend defined in previous work (Shera, 2003) for all age groups. Above 2 kHz, however, minimum spacings (maximal values of N_{SOAE}) deviate from this trend in the middle-aged/elderly group. According to the standing-wave model of SOAEs, broader SOAE spacings (smaller values of N_{SOAE}) are consistent with shorter OAE delays and broader frequency tuning. Although the reduced values of N_{SOAE} in the elderly appear qualitatively consistent with the broadened tuning

expected in the aging group, there are other, less interesting interpretations. For example, the data above 2 kHz in the elderly—and, for that matter, above 4 kHz in the other age groups—may simply be too sparse to reliably reveal the population trend. Figure 12 shows numerous SOAEs present in elderly subjects at high frequencies, but fewer than the other groups. Indeed, the number of SOAE pairs above 2 kHz for the middle-aged/elderly group is 56 (out of 110 total), whereas the teen/young-adult and newborn groups have nearly double this number above 2 kHz. In addition, few elderly subjects present the strings of closely spaced SOAEs needed to obtain accurate measures of minimum spacing. Thus, these data alone cannot determine whether the broadened tuning expected in elderly ears drives the apparent increase in SOAE minimum spacings seen here above 2 kHz.

The global standing-wave model, in which SOAEs arise as continuously self-evoking stimulus-frequency OAEs, predicts that SOAE minimum spacings are largely determined by stimulus-frequency OAE (SFOAE) phase gradients (e.g., Shera 2003, Figs. 3 and 4) and thus by the sharpness of frequency tuning. The model predicts that SOAE bandwidths also depend on SFOAE phase gradients, at least if the frequency jitter arises from fluctuations in stapes reflection. For example, Eq. (19) in Shera (2003) implies that fractional frequency deviations arising from changes in middle-ear stiffness depend inversely on N_{SFOAE} . We explore this prediction in Fig. 13, which shows a scatterplot of N_{BW} , defined as $f_0/\text{BW}_{\text{LE}}$. For each age group, the dashed lines show the best fitting power-law relation of the form $\beta(f/[\text{kHz}])^\alpha$. Parameters are $\ln\beta = \{6.1 \pm 0.3, 6.44 \pm 0.2, 6.46 \pm 0.2\}$ and $\alpha = \{0.39 \pm 0.3, 0.36 \pm 0.2, 0.35 \pm 0.2\}$ for the newborn, teen/young-adult, and middle/older groups, respectively; the uncertainties give the 95% confidence intervals. The smaller newborn value of β confirms that newborn SOAEs tend to have larger bandwidths. Comparing the values of α across

age groups shows that N_{BW} increases with frequency at nearly the same rate. In agreement with model predictions, the value of α matches that of N_{SFOAE} in humans almost exactly ($\alpha = 0.37 \pm 0.07$; Shera, 2003). The common frequency dependence of N_{BW} and N_{SFOAE} supports the model prediction that the same mechanisms that determine SFOAE delay and control the sharpness of cochlear frequency tuning also play a role in setting SOAE bandwidths.

Our study combined with the modeling studies that have come before suggest that automatic detection and modeling of the SOAE provides an effective means to identify and characterize spontaneous OAEs. SOAEs provide a window into cochlear mechanics that can reveal changes in cochlear function due to maturation, aging, and even hearing loss. Given that 65%–70% of normal young adult ears and nearly 85% of newborns have SOAEs, it appears that they are sufficiently available for detection and modeling. Further work investigating their relationship with cochlear health and sensorineural hearing loss is warranted.

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¹This mean SOAE level was calculated by converting each individual SOAE level to pressure and taking an average of pressure levels, then converting the grand average back to dB SPL. Hence, this mean value will not match exactly with the histograms in Fig. 3 that are in dB SPL (and have never been converted to pressure units.)

²SOAE level in this recent study cannot be directly compared to level in the archival SOAE records because the FFT frequency bins were different. Archival SOAEs were analyzed with 12 Hz resolution and the new SOAEs with 1 Hz resolution. By using the formula $10 \log_{10}(\text{BW})$, where BW is the estimated bandwidth of the SOAE and the reference BW is 1 Hz, one can approximate a correction to equate the two measures. When this is applied, a correction of ~ 7 dB is required though it varies slightly across age group. Therefore, newborns show levels closer to 16 dB SPL if one wishes to compare with much of the literature on SOAEs, and with the Archival results).

³For the purpose of spacing calculations (and to augment the SOAE pairs available for this analysis) we used a more liberal SOAE detection criteria of 2 SD above the noise.

⁴With a temporal resolution of only 1 s, our analysis was not sensitive to rapid fluctuations. We did, however, examine a representative sample of the data for slower temporal patterns. In some SOAEs found evidence for frequency (and level) modulations of a few Hz occurring over time intervals of 20–30 s. When present, these modulations often appeared correlated across SOAEs of similar frequencies in the same subject. Further study is needed to determine whether these slow modulations differ systematically across age groups, or can be correlated with modulations in other physiological responses.

FIG. 13. (Color online) Scatterplot of values N_{BW} vs SOAE frequency. N_{BW} is defined as f/BW_{LE} and represents the inverse fractional SOAE bandwidth. Age groups are identified by symbols. Solid lines show power-law fits to the individual group data (parameters given in the text). The dotted line shows the power-law approximation $N_{\text{SFOAE}} = 11.1(f/[\text{kHz}])^{0.37}$ to high-frequency SFOAE delay (in periods) reproduced from Fig. 3 of Shera (2003).

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