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Research Paper

Sweep-tone evoked stimulus frequency otoacoustic emissions in humans: Development of a noise-rejection algorithm and normative features

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ABSTRACT

In recent years, there has been a growing interest to measure stimulus frequency otoacoustic emissions (SFOAEs) using sweep tones. While there are several advantages of the sweep-tone technique, one of the major problems with sweep-tone methodologies is the lack of an objective analysis procedure that considers and rejects individual noisy recordings or noisy segments. A new efficient data-driven method for rejecting noisy segments in SFOAE analysis is proposed and the normative features of SFOAEs are characterized in fifty normal-hearing young adults. The automated procedure involved phase detrending with a low-order polynomial and application of median and interquartile ranges for data outlier rejection from individual recordings. The SFOAE level and phase were analyzed using the least-squared fit method, and the noise floor was estimated using the error of the mean of the sweep level. Overall, the results of this study demonstrated the effectiveness of the automated noise rejection procedure and described the normative features of sweep-tone evoked SFOAEs in human adults.

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1. Introduction

Stimulus frequency otoacoustic emissions (SFOAEs) are generated in response to an external acoustic stimulus at the same frequency as the stimulus. SFOAEs evoked by low-level pure-tones are generated via coherent reflection mechanisms—reflections from impedance irregularities at the peak of the traveling wave (Shera et al., 2008; Shera and Guinan, 2003, 1999), and are thought to reflect the functioning of cochlear amplifier gain. Their interpretation is relatively simpler compared to other types of emissions, in particular, distortion product otoacoustic emissions. SFOAEs can be useful for identification of sensorineural hearing loss (Ellison and Keefe, 2005) and are proposed to be the most suitable tool for measuring the dynamics of the medial efferent effects (Guinan et al., 2003). In addition, SFOAE delays have been used to objectively estimate cochlear frequency selectivity in humans and animals (Bentsen et al., 2011; Joris et al., 2011; Shera et al., 2010, 2002). However, measurement and analysis of SFOAEs present two main challenges. First, SFOAEs occur at the same frequency as the evoking pure tones, making them harder to extract. Second, SFOAEs are conventionally measured for one frequency at a time. As a result, measuring SFOAEs at a given frequency range of interest (e.g., 500–4000 Hz) takes a relatively long time, inherently due to the use of discrete pure tones. Longer test duration may lead to larger measurement noise, particularly for difficult-to-test populations, such as infants. Perhaps for these reasons, SFOAEs have not found widespread applications in the clinic despite their ability to inform about cochlear mechanisms.

In the discrete-tone procedure, SFOAEs are measured for one frequency at a time, whereas, frequencies are continuously varied in the sweep-tone technique. In the past decade, there has been a growing interest in applying sweep-tones for recording SFOAEs (Choi et al., 2008). The use of swept tones in conjunction with least-squares-fit (LSF), as used in this study, dates back to Long et al. (2008), with several promising reports with varied analysis methods appearing in the literature (Chen et al., 2013; Dewey and Dhar, 2017; Kalluri and Shera, 2013). Choi et al. (2008) applied a digital heterodyne technique for estimating SFOAEs. Chen et al. (2013) applied a tracking filter, i.e., a narrow band-pass filter whose center frequency can be dynamically tuned to the frequency

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of interest, and fast Fourier transform for obtaining SFOAE estimates. Kalluri and Shera (2013) compared Fourier analysis, digital heterodyning and LSF for obtaining estimates of SFOAE amplitude and phase, and reported that LSF is relatively less susceptible to noise in the waveform, though it is computationally more demanding among the methods. In addition, Kalluri and Shera (2013) showed that sweep- and discrete-tone methods of measuring SFOAEs yield nearly equivalent results. The differences between them are comparable to the test-retest variability encountered using either method. The match also appeared robust to variations in recording parameters, such as sweep rate and direction.

The sweep-tone method provides SFOAE data with fine-frequency resolution, which is critical for characterization of SFOAE group delay and amplitude fine-structure. Practically, high-resolution SFOAEs over three octaves (e.g., 500–4000 Hz) with a robust signal-to-noise ratio (SNR) can be recorded in less than 10 minutes in human adults (e.g., Chen et al., 2013; Kalluri and Shera, 2013). This salient feature makes SFOAEs even more attractive as a tool for probing cochlear function.

While SFOAEs evoked by swept tones significantly reduce the test duration, there are important problems in the analysis related to artifacts and/or recording noise that need to be addressed. Some of the main issues are slippage of the microphone in the ear canal over time, intermittent timing errors in the signal generation, and random noise sources that corrupt portions of the signal. Most certainly, consideration of these problems would greatly enhance the utility of SFOAEs in the clinic and laboratory, and would also contribute to the understanding of the sweep-tone method for recording OAEs.

Slow probe-microphone drifts in the ear canal may not produce noticeable noise in the recording; however, these drifts cause shifts in phase with the frequency associated with the change in the effective length of the ear canal. A robust method should not be adversely influenced by small shifts in the position of the microphone over time.

Transient and other types of physiologic noise are almost always present in the recorded sweeps. For example, noisy breathing, yawning, subtle movements of the subject and/or the microphone cable may be associated with the recording noise. One subjective approach to discard noise is to reject the entire sweep when it has significant noise in it. However, reducing the number of averages (sweeps) could potentially increase the noise floor of the measurements by as much as 3-dB. The method for rejection of noisy sweeps is often done manually, *cherry picking* the cleanest-looking sweeps. Manual selection not only requires tester expertise, but also impacts uniformity in the procedure, which could potentially bias the analysis, and diminish the reproducibility of the results because different researchers may select different criteria for inclusion of individual sweeps into the final analysis. A more efficient and less subjective procedure is needed for rejecting noise that allows a greater percentage of signal to be retained. This process should be automated, which will substantially reduce the time needed for data analysis. This will also enforce objective criteria for the rejection of noisy data.

Kalluri and Shera (2013) implemented a real-time method for removing noisy segments of sweeps using a thresholding criterion in the time domain that was adjusted for each subject. Similar approaches for removing artifacts were applied either online or post-hoc for measuring sweep-tone evoked distortion product OAEs (Abdala et al., 2015; Shera and Abdala, 2016). Such strategies likely improve the measurement quality, however, their effectiveness in improving SNR is unknown.

The current study describes the development of a new efficient method for analysis of sweep-tone evoked SFOAEs using the suppressor-tone paradigm and characterizes the normative features of SFOAEs in human adults. The proposed approach considers both amplitude and phase information from individual subject recordings for defining the noise rejection criteria.

2. Methods

2.1. Subjects

Of 54 human subjects screened for the study, 50 young adults (17 male and 23 female), 19–35 years of age (mean = 22.56 years), were chosen to participate. Participation criteria were: (1) hearing thresholds of 15 dB HL or better at octave frequencies from 250 to 8000 Hz and (2) normal tympanogram. All measurements were made in a sound-treated booth with the subject seated in a reclining chair. All procedures were approved by the Institutional Review Board, New Mexico State University.

2.2. Stimulus generation

Stimuli were generated digitally using a sampling rate of 44,100 Hz. The frequency of the probe tone was swept logarithmically in the range of 500–4000 Hz. The instantaneous frequency $f(t)$ of the logarithmic stimulus swept tone at time t is expressed as:

$$f(t) = f_{start}(f_{end}/f_{start})^{t/T} \tag{1}$$

$$\Rightarrow t = \frac{T}{\log(f_{end}/f_{start})} log(f(t)/f_{start}) \tag{2}$$

where f_{start} is the starting frequency, f_{end} is the ending frequency and T is the duration of the sweep.

The instantaneous total phase of the swept tone is expressed as:

$$\phi(t) = \frac{2\pi f_{start} T}{\log(f_{end}/f_{start})}(f_{end}/f_{start})^{t/T} + \phi(0) \tag{3}$$

Therefore, the swept tone waveform can be expressed as:

$$y(t) = a\ cos(\phi(t)) \tag{4}$$

where 'a' represents the amplitude of the stimulus.

The levels for the probe and suppressor tones were fixed at 40 and 60 dB SPLs, respectively. The iso-voltage stimulus-presentation scheme, that presents and maintains a constant voltage to the transducer over frequency, was used. The SPLs were established based on the calibrator measurement at 1000 Hz and extended to other frequencies considering the flat frequency response of ER-2 transducers (Etymotic Research, Elk Grove, IL). Individual differences in the ear canal geometry and tympanic membrane impedances could produce differences between the SPL in the ear canal and that in a coupler. These aberrations are not relevant for the frequencies tested here and are smaller than the discrepancies produced by calibrating at the position of the probe (Talmadge et al., 1999).

The ratio between suppressor and probe swept tone frequency was kept as 1.1, with suppressor frequency greater than the probe frequency (Johnson and Beshaler, 2013).

2.3. Suppressor signal paradigm

SFOAEs were estimated via the suppressor paradigm (e.g., Kemp and Chum, 1980; Kalluri and Shera, 2007). Probe and suppressor tones were swept in a two-interval paradigm. The sweeps consisting of both probe and suppressor tones were interleaved with the probe tones alone. In order to cancel the suppressor tone

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