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Research paper

Interrelationships between spontaneous and low-level stimulus-frequency otoacoustic emissions in humans

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ABSTRACT

It has been proposed that OAEs be classified not on the basis of the stimuli used to evoke them, but on the mechanisms that produce them (Shera and Guinan, 1999). One branch of this taxonomy focuses on a coherent reflection model and explicitly describes interrelationships between spontaneous emissions (SOAEs) and stimulus-frequency emissions (SFOAEs). The present study empirically examines SOAEs and SFOAEs from individual ears within the context of model predictions, using a low stimulus level (20 dB SPL) to evoke SFOAEs. Emissions were recorded from ears of normal-hearing young adults, both with and without prominent SOAE activity. When spontaneous activity was observed, SFOAEs demonstrated a localized increase about the SOAE peaks. The converse was not necessarily true though, i.e., robust SFOAEs could be measured where no SOAE peaks were observed. There was no significant difference in SFOAE phase-gradient delays between those with and without observable SOAE activity. However, delays were larger for a 20 dB SPL stimulus level than those previously reported for 40 dB SPL. The total amount of SFOAE phase accumulation occurring between adjacent SOAE peaks tended to cluster about an integral number of cycles. Overall, the present data appear congruous with predictions stemming from the coherent reflection model and support the notion that such comparisons ideally are made with emissions evoked using relatively lower stimulus levels.

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1. Introduction

Sounds evoked from the ear, known as otoacoustic emissions (OAEs), provide a noninvasive window into the mechanics of hearing (Probst et al., 1991) and are readily measurable across a wide range of species (Koppl, 1995). Furthermore, the ears of many normal-hearing individuals emit spontaneously (SOAEs) (Kemp, 1979; Zurek, 1981). In humans, these emissions tend to be narrow-band in nature, spectrally unique to a given ear, and relatively stable over long periods of time (Burns, 2009). Additionally, SOAEs have been shown to demonstrate statistical properties consistent with self-sustained sinusoids (Bialek and Wit, 1984; Shera, 2003), suggestive as evidence for an amplification process at work in the ear. However, the study of SOAEs for evaluating cochlear status has been limited, presumably due to their relatively low incidence in normal-hearing individuals: human SOAEs occur in roughly 60–80% of women and 25–60% of men (Moulin et al., 1993; Whitehead et al., 1993; Talmadge et al., 1993).[1] When SOAEs are present, they are typically sparsely distributed and at idiosyncratic frequencies, making them difficult to use for audiological screening purposes.

Evoked emissions (eOAEs) have demonstrated clinical value (Probst et al., 1991) and are thus more commonly measured than SOAEs. Traditionally, distortion-product and transient-evoked OAEs (DPOAEs, TEOAEs) are routinely examined, despite complexities associated with their generation stemming from the multi-frequency evoking stimuli and the nonlinearity of the cochlea. For

Abbreviations: DPOAE, distortion-product otoacoustic emission; eOAE, evoked otoacoustic emission; N_{SFOAE}, SFOAE phase-gradient delay expressed in stimulus periods; N_{SOAE}, geometric mean frequency between adjacent SOAE peak pairs divided by their frequency separation; RR_{stapes}, product of the reflectances at the peak of the traveling wave and the stapes; SFOAE, stimulus-frequency otoacoustic emission; SOAE, spontaneous otoacoustic emission; TEOAE, transient-evoked otoacoustic emission.

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[1] Quantitatively, the precise incidence depends strongly upon the detection method employed (e.g., microphone noise, averaging technique) (Talmadge et al., 1993). Racial differences in SOAE incidence have also been noted (Whitehead et al., 1993), as well as lateralization (SOAEs are more common in the right ear rather than the left) (Burns et al., 1992; Kulawiec and Orlando, 1995) and variations with heartbeat (Long and Talmadge, 1997).

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example, DPOAEs have been demonstrated to arise from at least two distinct sources in the cochlea, both of which can interfere in a complex fashion (Talmadge et al., 1998). Less commonly measured are stimulus-frequency otoacoustic emissions (SFOAEs), arguably the simplest type of evoked emission, arising in response to a single stimulus tone (Kemp, 1980; Zwicker and Schloth, 1984; Martin et al., 1988; Zwicker, 1990; Shera and Zweig, 1993; Kalluri and Shera, 2007b). SFOAEs have been recently demonstrated to objectively provide estimates of cochlear filter tuning bandwidths (Shera et al., 2002; Joris et al., 2011). However, technical difficulties associated with their measurement have limited their study,[2] as has controversy over interpretation of SFOAE generation (e.g. Siegel et al., 2005).

Previous theoretical studies have suggested that low-level SFOAEs arise primarily from a linear process of coherent reflection (Zweig and Shera, 1995; Talmadge et al., 2000). These reflections are hypothesized to arise due to random perturbations along the cochlea, or an inherent roughness of the cochlear partition (Lonsbury-Martin et al., 1988). A taxonomy classifying emissions posits that SOAEs and SFOAEs arise fundamentally from the same mechanism (Shera and Guinan, 1999), SOAEs being a special self-sustained case where the cochlea behaves in a manner analogous to a laser-cavity (Shera, 2003). While such a hypothesis was tested empirically and found to hold well (Shera, 2003), a stimulus (probe) level of $L_p = 40$ dB SPL was used to evoke the SFOAEs in that study. As motivated by previous studies (Neely et al., 1988; Zweig and Shera, 1995), Shera (2003) argued for an “intensity correction” to the data, a step that should be unnecessary if a lower probe level is used. Another motivation for using lower stimulus levels stems from the nonlinear nature of the cochlea. In light of empirical observations that mammalian basilar membrane growth functions are linear for low stimulus levels, but become compressive above $\sim$20–30 dB SPL (Ruggero et al., 1997), a moderate stimulus level of $L_p = 40$ dB SPL may introduce nonlinear effects that could confound relating data to model predictions. In fact, human SFOAE phase-gradient delays have been shown to increase further with decreasing stimulus level (Zweig and Shera, 1995; Schairer et al., 2006; Bergevin, 2007), though delays have not been examined in detail for stimulus levels below 40 dB SPL. One additional consideration is that comparisons between SOAEs and SFOAEs made by Shera (2003) were examined in grouped data pooled across subjects, not data from individual ears. Such comparisons in individuals would provide additional ways to test model predictions, by quantifying features such as how SFOAE phase changes about and between adjacent SOAE peaks.

The goal of the present study is to examine several questions within the context of SOAEs and SFOAEs interrelationships, as motivated by the coherent reflection (Zweig and Shera, 1995) and global standing wave models (Shera, 2003) for emission generation. Specifically:

- What correlations exist between SOAEs and SFOAEs in individual ears? For example: Do SOAEs occur where SFOAE magnitudes are largest? How much SFOAE phase accumulation occurs between SOAE peaks?
- How do SFOAEs compare between subjects with and without strong SOAE activity?
- How do the properties of SFOAEs evoked with lower stimulus levels (20 dB SPL) compare to results of other studies using similar methods, but higher stimulus levels (e.g., 40 dB SPL)?

Regardless of any specific model, addressing these empirically-based questions will shine further light upon the biophysical mechanisms at work in the ear responsible for OAE generation.

2. Methods

2.1. Measurement system

All measurements reported here were obtained using similar methods as those reported previously (Shera and Guinan, 1999; Bergevin, 2011). A desktop computer housed a 24-bit soundcard (Lynx TWO-A, Lynx Studio Technology), whose synchronous root mean square (RMS) input/output was controlled using a custom data-acquisition system. A sample rate of 44.1 kHz was used to transduce signals to/from a probe containing an Etymotic ER-10A microphone and two ER2-A earphones.[3] The microphone was calibrated using a pistonphone (Brüel and Kjær, type 4230). For OAE experiments, mic responses were amplified by 40 dB and high-pass filtered with a cut-off frequency of 0.41 kHz to minimize the effects of noise. The OAE probe was coupled to the external ear by means of either a foam or a rubber tip. This ensured a tight (closed) acoustic coupling and minimized low-frequency losses (<1 kHz). The probe earphones were calibrated in-situ by presenting flat-spectrum, random-phase noise. Calibrations were verified repeatedly throughout the experiment. All stimulus frequencies were quantized such that an integral number of cycles were contained within the sampling window. All testing was conducted in a sound-attenuating booth.

2.2. Measurement and analysis paradigm

Subjects were typically seated quietly in the booth for an initial period of at least 10–15 min before testing (Whitehead, 1991). SOAE data were typically collected at the start of an experiment, though in several cases they were collected both before and after SFOAE data collection. No differences were generally seen in those cases. A total of 60 waveforms (32,768 sample window, SR = 44.1 kHz) were acquired and the FFT magnitudes spectrally averaged, either with or without a suppressor tone present. The presence of SOAE peaks was typically confirmed by presenting a nearby tone (40 dB SPL) and observing suppression.

For SFOAEs, the range of stimulus frequencies (f_p) employed was typically 0.5–5 kHz, depending upon the location of SOAE activity. The frequency step of $\sim$15 Hz was chosen as a compromise between obtaining SFOAE data in a reasonable amount of time and trying to avoid ambiguities in phase unwrapping (particularly about SOAE peaks, where SFOAE phase can rotate rapidly). The stimulus and emission frequency are one and the same for SFOAEs. A two-tone suppression paradigm was employed to extract the SFOAE (Shera and Guinan, 1999). A stimulus level of $L_p = 20$ dB SPL was used. The suppressor parameters were: $f_s = f_p + 40$ Hz, $L_s = L_p + 15$ dB (where f_s and L_s are the suppressor frequency and level, respectively). It is noted that while a previous SFOAE study (Kalluri and Shera, 2007b) examined low stimulus levels ($L_p \leq 40$ dB SPL), in contrast to the present study they used a fixed suppressor level ($L_s = 55$ dB SPL). The reasoning for using a fixed $L_s - L_p$ (and thereby $L_s = 35$ dB SPL) here was that, given the

[2] SFOAEs arise at the same frequency as the stimulus being used to evoke them, thereby making them difficult to extract. Typically a suppression paradigm is employed (see Methods), but such a method can be more sensitive to nonlinearities associated with the measuring earphone(s) and mic. However, there are numerous other methods by which SFOAEs can be extracted, all leading to the same result when low stimulus levels are employed (Kalluri and Shera, 2007a).

[3] A small subset of data, not included in the final analysis, was also obtained using an ER-10C. Similar results for a given ear were obtained from both probe assemblies.