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A fast algorithm for the measurement of stimulus frequency otoacoustic emission suppression tuning curves

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ABSTRACT

Frequency selectivity is an important indicator of auditory function in the human ear. Stimulus frequency otoacoustic emission (SFOAE) suppression tuning curves (STCs) have great potential in the objective analysis of human auditory frequency selectivity but are costly to measure by the traditional algorithm using pure-tone adaptive method. To improve the measurement efficiency of the SFOAE STCs, a faster algorithm based on a suppressor with gradiently changing intensity and interpolation is proposed in this paper. Twelve subjects participated in this study by measuring their SFOAE STCs through the traditional and fast algorithm. The results shows that the average correlation coefficients of the SFOAE STCs measured using the fast and the traditional algorithms at different probe frequencies is 0.94. And the measurement speed of the fast algorithm was approximately 2.10 times higher than the traditional one. Also, the fast algorithm is more efficient than the algorithms of Keefe et al. (2008) and Charaziak et al. (2013). Experimental evidence is provided that the proposed fast algorithm greatly improves the measurement speed and reduces the processing time, exhibiting good accuracy and reliability.

1. Introduction

Frequency selectivity, which refers to the ability of the auditory system to filter one certain stimulus out from a complex sound of different frequencies [3], largely depends on the filtering function of the cochlea [4]. Frequency selectivity is one of the most basic features for perception of complex sounds, e.g., speech in noise [5]. Frequency selectivity tuning at low to moderate levels of stimulation is determined by the amplification mechanisms of the cochlear outer hair cells (OHCs) [6–8]. And at moderate to high levels of sound, it is determined by the mechanical properties of the basilar membrane damped by the fluid. Both frequency selectivity and the sensitivity of the auditory system will be reduced if the OHCs are damaged [9–14]. Experiments have demonstrated that the reduction or loss of the frequency selectivity of mammals' auditory system, such as guinea pigs and chinchillas, reflects the damage to their auditory systems [5]. In humans, the reduction of the frequency selectivity will cause the loss of the ability to sense complex sounds and music [5]. Consequently, the estimation and study of frequency selectivity can assess OHCs function and has a significant effect on the comprehension of complex sound perception. So, it has been suggested that including frequency selectivity measures in the clinical test battery may improve diagnostics and counseling [15,16].

With regard to animals, their frequency selectivity can be directly evaluated through their basilar membrane or auditory nerve fibers; however, these methods are not suitable for human beings because of their invasiveness. Therefore, to assess frequency selectivity in humans, behavioral methods are generally applied. For example, currently, the use of psychophysical tuning curves (PTCs) is a popular approach that uses psychoacoustic detection of masked signals [17] to obtain the tuning curves. Specifically, a probe tone with a certain frequency and intensity was delivered to the ear of the subject, and simultaneously, the central frequency and intensity of the masker were changed to exactly cover the probe tone, forming a V-shaped curve [18]. Although it is proved by many studies that PTCs measured simultaneously with the masker is a valid approach to assess the frequency selectivity, the approach cannot be applied to all groups, especially people who are difficult to cooperate with [19], such as infants, because of the PTCs' subjectiveness [20]. Recently, the stimulus frequency otoacoustic emission (SFOAE) suppression tuning curves (STCs) have attracted special attention [1,2,21–24]. It is based on SFOAE, which is a kind of OAE evoked by one single tone that has the same

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frequency as the stimulus [25–28]. SFOAE appears to be well suited for assessing frequency selectivity because the originate over a restricted region of the cochlea near the characteristic place of the evoking tone [23]. SFOAE STCs are curves describing the relationship between the intensity and frequency of the suppression under the same inhibition criterion using a suppression-based mode similar to simultaneous masking [29]. Kemp and Chum [30] first predicted that SFOAE STCs could potentially be used to objectively evaluate the periphery auditory system. Subsequently, it has been shown that SFOAE STCs are as sharply tuned as auditory nerve fiber tuning curves in mice [21], and SFOAE STCs and CAP-STCs show similar tuning in chinchillas [22]. Further, estimation of frequency selectivity provided by SFOAE STCs in humans and that provided by behavioral measures of PTCs indicate similar characteristics [2,30]. Therefore, SFOAE STCs have the potential to assess the frequency selectivity in a noninvasive, objective and effective way [29].

Except SFOAE STCs, SFOAE phase data can be also used to estimate the frequency selectivity noninvasively and objectively [25,31–34]: The SFOAE group delays, τ_{SFOAE}—defined as the negative of the slope of the emission-phase versus frequency function—can be calculated from unwrapped phase responses and be expressed in dimensionless form as the equivalent number, N_{SFOAE}, of stimulus periods. Then Q_{ERB}, which represents cochlear frequency selectivity, can be calculated by $Q_{ERB} \equiv kN_{SFOAE}$ [34]. But k is an empirical value depending on the characteristic frequency, so the frequency selectivity got in this way is a speculation instead of a direct result. Therefore, besides noninvasion and objectiveness, direct assessment of frequency selectivity is also an advantage of SFOAE STCs.

However, the common measurement method of SFOAE STCs used by Charaziak et al. [2,23], Cheatham et al. [21], Brass et al. [35]and Kemp et al. [36] is time-consuming. Obtaining one curve may require hundreds of single SFOAE measurements to ensure the high signal-to-noise ratio. In the test of frequency selectivity, it generally requires at least one hour to obtain the results of four curves of SFOAE STCs at 1 kHz and 4 kHz for both ears, which reduces the test efficiency. Meanwhile, the longer the subject sits in the closed shielding room to take tests, the worse the subject cooperates, leading to the need for repeated measurement and a lower accuracy.

Therefore, taking into consideration the subjects' fatigue and the accuracy of the collected data, the overall test time should be reduced. Although there are several fast algorithms for SFOAE measurement [37–39], no fast algorithm for SFOAE STCs measurement has been proposed yet. This paper proposed a faster algorithm of SFOAE STC measurement to improve the efficiency of the SFOAE STCs measurement. The experimental results of eleven subjects showed that our proposed method could reduce the acquisition time from 13 min on average by the traditional method (which is described in Section 2.3) to less than 7 min per SFOAE STC. In addition, experimental evidence was provided that the accuracy and stability of our new measurement method of SFOAE STCs was good.

2. Methods

2.1. Experimental equipment

A probe assembly with two miniature ER-2 loudspeakers (Etymotic Research) and an ER-10B+ microphone (Etymotic Research) is inserted in the subject's ear. The ER-2 earphones are used to present the two stimuli in Fig. 1A: earphone A plays probe p, and earphone B plays suppressor s_1, s_2, …, s_{10}. The acoustic responses in the ear canal are recorded by the ER-10B+ microphone and converted to electrical signals. Next, these signals are amplified and digitized by a Fireface 800 soundcard (RME). The signal presentation and acquisition are controlled by a PC program implemented in C# and MATLAB.

2.2. Participants

Twelve subjects (22–30 years old) participated in this study. All of the subjects were native Chinese speakers and university students at Tsinghua University. The subjects had no history of outer or middle ear problems and normal hearing thresholds (<20 dB HL for octave frequencies of 250–8000 Hz). The subjects were seated in a sound-proofed room comfortably and were instructed to be as quiet as possible during the test. All subjects gave their written informed consent to participate, in compliance with a protocol approved by the institutional review board of Tsinghua University.

2.3. Experimental procedures

2.3.1. Stimulus method

A probe tone (p) and an intermittent suppressor tone (s_1, s_2, …, s_{10}) with gradiently changing intensity were used to measure SFOAE STCs in this study. Fig. 1A shows the stimuli synthesis of each trial during 10T. The probe tone p's frequency and intensity and the suppressor tone s's frequency were fixed. The suppressor tone was composed of ten segments (each segment's duration is T): s_1, s_2, …, s_{10}, whose intensity were L_{pre}-16, L_{pre}-12, L_{pre}-8, L_{pre}-4, L_{pre}, L_{pre}+4, L_{pre}+8, L_{pre}+12, L_{pre}+16, and L_{pre}+20 dB SPL, respectively. While L_{pre} is the prediction of the suppressor level that we attempt to obtain and is piecewise fitted by the average of SFOAE STCs data (as Fig. 1B shows) measured by the traditional algorithm from a different group of 25 subjects reported by Qin Gong et al. [29] and Yao Wang et al. [40]; the fit is given as follows using a quadratic and a cubic function separately and is shown in Fig. 1B:

$$L_{pre} = \begin{cases} -59.1*(f_s/f_p)^2 + 41.45*f_s/f_p + 61.51 + (l_p-30)/2 & (f_s < 1.15f_p) \\ -225.6*(f_s/f_p)^3 + 946.6*(f_s/f_p)^2 - 1221*f_s/f_p + 526.4 + (l_p-30)/2 & (f_s \geqslant 1.15f_p) \end{cases} \tag{1}$$

where fp and fs are the frequencies of the probe tone and the suppressor tone, respectively. And lp represents the intensity of the probe tone.

A two-tone suppression method of Brass and Kemp [35] was used to record the SFOAEs. Fig. 1C shows the stimuli synthesis for SFOAE acquisition in each segment T. There was one section of $2T_d$ in duration, following five T_w sections in each segment. T_d was the measurement system delay (acoustic and processing delay), which was 14.5 ms measured in advance. T_w is in inverse proportion to the frequency resolution of the signal recorded from the ear canal, which is 50 ms when the frequency resolution was 20 Hz. And the sampling rate was 48 kHz. Sections A, B, C and D of the pure-tone probe had the same polarity. The suppressor was a burst tone, whose rise and decay times were windowed by a 5-ms cosine window. Section D of the suppressor had an inverted initial phase to section C.

Therefore, the residual SFOAE for each segment is represented as Eq. (2):

$$\begin{aligned} residual &= (A+B) - (C+D) \\ &= (Rp + SFE) + (Rp + SFE) - (Rp + Rs + SFE') \\ &\quad - (Rp - Rs + SFE') = 2SFE - 2SFE' \end{aligned} \tag{2}$$