33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

# Hearing Level Equalized Otoacoustic Emissions Acquired by Swept-Tones: Intensity Characteristics

Todor Mihajloski, Magdalena Lachowska, Christopher L Bennett, Ozcan Ozdamar, *Member, IEEE*

*Abstract*— **Otoacoustic emissions (OAE), which are acoustic responses produced by the cochlea, can be recorded with a microphone in the ear canal to give diagnostic information regarding cochlear functioning. Recently, the researchers developed a novel stimulus for the acquisition of OAE using a hearing-level equalized ($HL_{eq}$) swept-tone signal. The objective of this study was to observe OAE characteristics at a multitude of intensities to track the changes in temporal and spectral morphology. An increase in high-frequency emissions was found as stimulation intensity decreased. Furthermore, it was found that hearing level equalized swept-tone OAEs ($HL_{eq}$ sTEAOE) can be acquired at very low intensities, which is not typical under current acquisition modalities. This may result in clinical improvements by providing a fast and cheap method for contributing to the detection of auditory thresholds.**

## I. Introduction

Transient-evoked otoacoustic emissions (TEOAE) are generated within the cochlea in the inner ear in response to acoustic stimuli commonly clicks or tone bursts. They are acquired by averaging post-stimulus acoustic responses which are recorded in the external ear canal. The presence of TEOAE indicates normal cochlear functioning. Recently, a novel method for acquiring otoacoustic emissions (OAEs) was described [1,2], in which a new long duration stimulus, called swept-tone (100 ms) was used to elicit a cochlear response that was comparable to TEOAE (Fig. 1). In swept-tone TEOAE (sTEOAE), the stimulus frequency is constantly rising and due to this feature at any instantaneous moment there is only a single frequency presented to the ear. However, through some post-processing techniques the response can be displayed as an impulse response which closely resembles a click-evoked TEOAE in phase and time-frequency domain characteristics.

The analysis method uses an increasing frequency tone (swept-tone) in conjunction with an inverse swept-tone in order to extract the impulse response of the acoustical signal. Using a deconvolution process, the swept-tone response (including OAE response) is compressed to a single impulse and an impulse response. The resulting impulse response contains two major components: 1) the meatal response (MR) from the ear canal; and 2) the OAE response. This method is useful for its ability to separate linear from nonlinear responses, its improved signal to noise ratio (SNR) over the standard click methods [3], and its ability to remove synchronized spontaneous OAEs from the recording.

The swept-tone stimulus can be equalized to match hearing level (HL) output intensities. The swept-tone stimulus contains only a single frequency component at any instantaneous point in time. Therefore, the level of any frequency can be adjusted with the use of a simple amplitude envelope to create a hearing level equalized ($HL_{eq}$) sTEOAE response. This study focuses on the intensity characteristics of $HL_{eq}$ sTEOAE responses.

## II. Materials and Methods

### A. Subjects

Ten normal hearing (<25 dB HL; audiometric test administered by a practicing audiologist) adult subjects were involved in this prospective study, 20 total ears were tested. Before performing $HL_{eq}$ sTEOAE recordings, all subjects were tested for transient OAE responses using a 100µs click at 75dBSPL on both ears. Their hearing levels were determined using a standard audiometry (Intelligent Hearing Systems, Miami, FL, USA). After determining that all subjects had no hearing loss and transient click TEOAEs were detected, the subjects were tested for the $HL_{eq}$ sTEOAE.

### B. Experimental Design

*1) Stimuli:* Since the swept-tone stimulus is defined temporally by an exponentially increasing frequency argument, the instantaneous frequency at any sample is given by the equation:

$$n(f) = N\frac{\log\left(\frac{f}{f_1}\right)}{\log\left(\frac{f_2}{f_1}\right)} \qquad (1)$$

Manuscript submitted April 15, 2011.

T. Mihajloski is with the Department of Biomedical Engineering, University of Miami, Coral Gables, FL, USA (phone: 305-284-5272; fax: 305-284-6494; email: t.mihajloski@umiami.edu).

M. Lachowska is supported by Polish-American Fulbright Commission as Fulbright Senior Advanced Research Grantee with the Department of Biomedical Engineering, University of Miami, Coral Gables, FL, USA. Her home affiliation is the Department of Otolaryngology, Medical University of Warsaw, Warsaw, Poland.

C.L. Bennett is with Department of Anesthesiology, Miller School of Medicine, University of Miami, Miami, FL and the Department of Biomedical Engineering, University of Miami, Coral Gables, FL.

O. Ozdamar is the corresponding author. He is with Department of Biomedical Engineering, University of Miami, Coral Gables, FL, USA, and Departments of Otolaryngology, Pediatrics and Neuroscience (graduate) Miller School of Medicine (secondary), University of Miami, Miami, FL, USA (email: oozdamar@miami.edu)

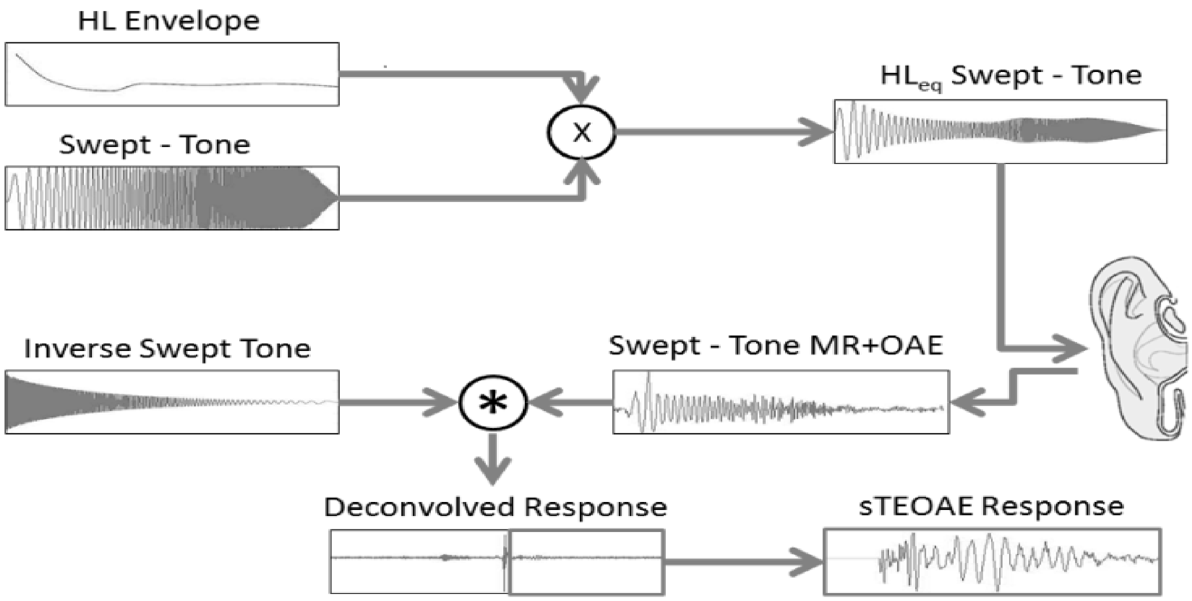


Fig. 1. HLeq sTEOAE acquisition. The Hearing Level Equalized ($HL_{eq}$) Swept-Tone stimulus is presented to the subject's ear using an OAE probe. The probe records the response using high bit-depth ADC. The response is convolved with the inverse swept-tone to produce the deconvolved impulse response. The linear and nonlinear components can be separated through windowing.

where $n(f)$ is the sample location for frequency $f$. $N$ is the length of the swept-tone stimulus in samples, $f_1$ is the start frequency, and $f_2$ is the end frequency. By implementing this equation, frequency-specific calibration values can be applied to the swept-tone stimulus. In this study, the calibration of a swept-tone stimulus to achieve hearing level equalized stimulation was accomplished by using the conversion values listed in Table I.

*2) Measures and Measurement Devices:* The recordings were performed using an Analog Devices ADSP-21369 SHARC EZ-KIT Lite Evaluation Kit based on the ADSP – 21369 Digital Signal Processing (DSP) core and a SHARC® Processor. The DSP system was controlled using Matlab® via RS-232 serial port. The probe used was an Etymotic Research (Elk Grove Village, IL) ER-10D OAE Probe. The setup included a 20 dB amplifier to magnify the signal from DSP output levels to the required levels for the 10D OAE probe, so combined maximum output of the system was 106 dB SPL. The microphone from the 10D OAE probe was directly connected to the input of the DSP. Both, the stimulus and the response, were sampled at 48000 samples per second and 24 bits per sample [4]. All of the recordings were performed in a booth isolated from electromagnetic interference and external sounds.

*3) Data Acquisition:* The recording of the $HL_{eq}$ sTEOAE was done using a 100 ms swept tone stimuli for 512 epochs at a rate of 7.9 epochs per second. Recordings were performed on both ears at 55, 45, 35, 25, and 15 dBHL with an $HL_{eq}$ swept tone stimulus. The stimulus artifact (meatal response) was eliminated from the recordings by using the derived nonlinear residue (DNLR) technique by acquiring three epochs at a set intensity and one epoch three times larger in amplitude and inverted with respect to the previous three [5]. The acquired epochs were averaged and stored in two buffers using the split buffer method, where even epochs are averaged in one buffer and odd epochs in a different one. The DNLR was also taken into consideration so the fourth epoch was alternated between the two buffers.

### *C. Data Analysis*

The deconvolved buffers were plotted together with their average for every recording. This allows for visual inspection of the recordings to determine their quality and inspect for possible problems like improper probe placement. The noise was extracted by taking the difference of the two deconvolved buffers. Both the signal and the noise were converted into the frequency domain using FFT and were plotted one on top of the other for visual inspection of the spectrum. In addition to this, the signal to noise ratio (SNR) was calculated for the entire waveform and for individual frequency bands (500, 1000, 1500, 2000, 3000, and 4000 Hz).

TABLE I
THE CONVERSION VALUES FROM SPL TO HL (ISO 226:2003)

| Frequency (kHz) | .25 | .5 | 1 | 1.5 | 2 | 3 | 4 | 6 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| SPL to HL (dB) | +27 | +13.5 | +7.5 | +7.5 | +9.0 | +11.5 | +12 | +16 | +15.5 |

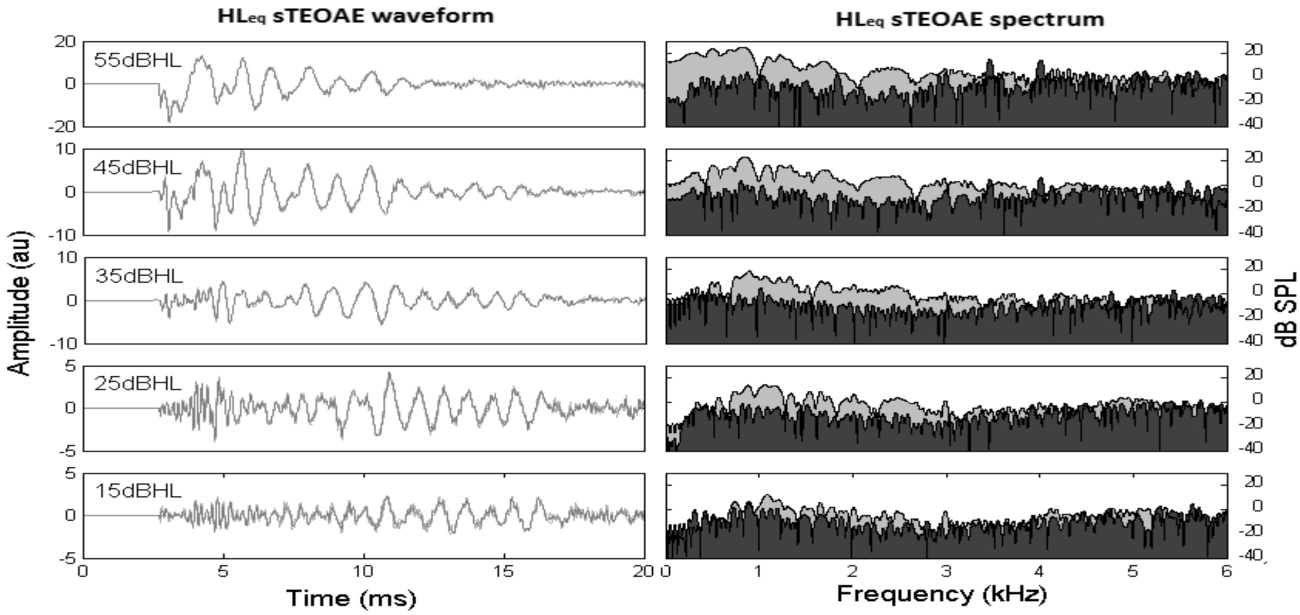


Fig. 2. $HL_{eq}$ sTEOAE responses for a single ear of one subject over a series of intensities. $HL_{eq}$ sTEOAE waveform and its spectrum are displayed on the left and right, respectively. Light and dark gray areas represent signal and noise, respectively.

## III. Results

Figure 2 shows the $HL_{eq}$ sTEOAE responses for a single subject over a series of intensities. The stimulus was kept constant, except for the intensity which was varied in steps of 10 dB from 15 dB HL to 55 dB HL. The time plots as well as the magnitude plots were obtained in order to visualize the change in morphology of the response both temporally and spectrally. It can be seen that at high intensities, the late-latency responses are obscured and the low-frequency sTEOAE and meatal artifact dominate the response. The meatal artifact is evident in the spectral plots, as no sTEOAE responses are expected below 0.5 kHz, so energy in this band can be assumed to be artifact.

TABLE II
The average of SNR values and standard deviation for six frequency bands derived from all 20 tested ears for $HL_{eq}$ sTEOAE responses over a series of intensities

| Intensity (dB HL) | Average SNR and standard deviation (dB) 500 Hz | 1000 Hz | 1500 Hz | 2000 Hz | 3000 Hz | 4000 Hz |
|---|---|---|---|---|---|---|
| 55 | 16.8 (6.4) | 15.9 (6.1) | 13.7 (5.3) | 11.5 (4.7) | -3.5 (5.3) | -5.3 (5.9) |
| 45 | 9.2 (5.8) | 12.7 (6.8) | 9.8 (6.7) | 10.4 (7.0) | 1.8 (6.5) | -1.0 (5.2) |
| 35 | 1.3 (4.2) | 6.2 (6.6) | 5.4 (5.9) | 7.4 (6.8) | 3.8 (6.4) | -1.1 (5.6) |
| 25 | -2.3 (4.1) | 2.9 (7.5) | 2.1 (5.5) | 3.3 (6.5) | 2.6 (5.0) | -2.4 (4.6) |
| 15 | -4.2 (3.4) | -1.6 (4.7) | 0.5 (3.9) | 1.0 (4.6) | 1.3 (2.6) | -5.2 (4.4) |

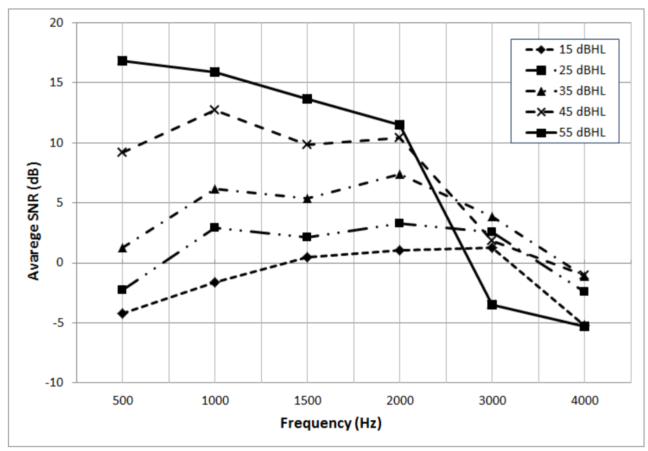


Fig. 3. The average of SNR values for six frequency bands derived from all 20 tested ears for $HL_{eq}$ sTEOAE responses over a series of intensities.

Figure 3 also shows the presence of a meatal artifact for the high intensity stimuli. The growth of OAE response amplitude is expected to be compressive, however the change in OAE response SNR from 55 dB HL to 45 dB HL at the low-frequencies is approximately 10 dB, indicating that this change is likely due to acoustic meatal artifact, as opposed to physiological cochlear response. However, as the intensity of the stimulus is decreased, parity in amplitude between early and late latency responses can be observed. In particular, at the lowest intensity a characteristic high-to-low frequency dispersion can be observed. Presence of low-intensity OAEs is notable, as it is not typical to find responses at such low stimulation intensities with a click stimulus. The average values and standard deviation of SNR derived from all 20 tested ears $HL_{eq}$ sTEOAE responses over a series of intensities are shown in Table II.

## IV. Discussion

This study investigates further improvements of using a calibrated swept-tone stimulus, which mimics an idealized acoustic click after deconvolution. Because of spatial recruitment of hair cells as well as temporal integration within the cochlea, it is difficult to make comparisons between transient stimuli (e.g., click) and steady-state stimuli (e.g., swept-tone). For this reason, hearing level (HL) calibrations were used, resulting in an amplitude envelope that mimics HL pure-tone magnitude equalization curves. This results in a new HL-equalized ($HL_{eq}$) swept-tone stimulus. Applying an amplitude envelope can equalize the magnitude of a swept-tone stimulus. The frequency of swept-tone stimulus is dispersed, and each instantaneous temporal location of post-stimulus onset is defined by a single deterministic frequency. This property allows for the mapping of the frequency-dependent intensities of the equal hearing level contours to the time-dependent intensities of the swept-tone stimulus.

Several advantages of the swept-tone OAE responses have previously been explored, and include improved SNR and reduced acquisition time compared to a click TEOAE responses. However, in this study it is shown that the swept-tone stimulus also elicits an OAE response even at very low intensities. While click OAE responses are not readily obtained at very low stimulation levels (e.g., 25 dB HL), most subjects (12 ears from 20 tested) in our study did exhibit OAE responses. This may be advantageous in clinical settings in hearing diagnostics and screening. Typically only ABR or ASSR methods are used for objective auditory threshold determination. The disadvantage of ABR and ASSR threshold detection methods is that the preparation and acquisition time is very high compared to an OAE test (60 to 90 minutes compared to 30 minutes). The swept-tone method may provide a new clinical tool for audiologists to quickly evaluate cochlear functioning at very low stimulation intensities, resulting in shorter visits and reduced hearing healthcare costs.

## V. Conclusions

The advantages of $HL_{eq}$ sTEOAE described above may have several beneficial implications in clinical applications, especially in hearing screening. Since $HL_{eq}$ sTEOAE presented beneficial noise properties, such as improving the signal-to-noise ratio in multiple frequency bands, they potentially may reduce the number of false positive results in hearing screening thus reducing costs. Furthermore, it was found that swept-tone OAEs can be acquired at very low intensities, which is not typical under current acquisition modalities. This may result in clinical improvements by providing a fast and cheap method for contributing to the detection of auditory thresholds. Further studies involving normal and hearing loss subjects are needed to validate the clinical usefulness of the presented method.

## Acknowledgment

The authors would like to gratefully acknowledge all the participants in this study, in addition to the assistance from Dr. Jorge Bohorquez. Dr. Magdalena Lachowska was conducting this research with the support from Polish-American Fulbright Commission as Fulbright Senior Advanced Research Grantee with the Department of Biomedical Engineering at the University of Miami.

## References

[1] C.L. Bennett, O. Ozdamar, "Swept-tone transient-evoked otoacoustic emissions", J Acoust Soc Am, vol. 128(4), pp.1833-1844, 2010.

[2] C.L. Bennett, "Acquisition of Otoacoustic Emissions Using Swept-Tone Techniques", PhD Dissertation, University of Miami, 2010.

[3] C.L. Bennett, D. Harris, A. Tankanow, R. Twilley R, "Effects of oversampling on SNR using swept-sine anlaysis", *Proc 129th Audio Eng Soc Con*, 4-7 Nov 2010: Preprint 8232, 2010.

[4] C.L. Bennett, O. Ozdamar, :High resolution systems for improved transient – evoked otoacoustic emmissions acquisition", *Proc 31st Ann Inter Conf IEEE EMBC*, Minneapolis, MN, 2009.

[5] D. Kemp, S. Ryan, P. Bray, "Otoacoustic emission analysis and interpretation for clinical purposes", Adv Audiol, vol. 7, pp. 77-98, 1990.