Available online at www.sciencedirect.com

ScienceDirect

Hearing Research 237 (2008) 66–75

Hearing Research

www.elsevier.com/locate/heares

Research paper

Contralateral suppression of distortion product otoacoustic emissions and the middle-ear muscle reflex in human ears

Xiao-Ming Sun *

Department of Communication Sciences and Disorders, Wichita State University, 1845 Fairmount Street, Wichita, KS 67260-0075, USA

Received 17 May 2007; received in revised form 28 November 2007; accepted 18 December 2007
Available online 28 December 2007

Abstract

Distortion product otoacoustic emissions (DPOAEs) were measured in the absence and presence of contralateral noise at five levels—below, equal to, and above the middle-ear muscle (MEM) reflex threshold. The resultant changes in DPOAE level and phase were dependent on stimulus frequency and noise level. Both low-level noise, believed to elicit the medial olivocochlear (MOC) reflex, and high-level noise, thought to activate both MOC and MEM reflexes, significantly decreased the DPOAE level. However, the shift from sole MOC effect to mixed MOC and MEM effects was not as dramatic as we thought. While low-level noise resulted in a minimum DPOAE phase change, high-level noise caused a substantial phase lead for 1 and 2 kHz. With increasing frequency, phase lag became more notable. The present study suggests the following: (1) DPOAE contralateral suppression by low-level sound most likely does not involve the effect of the MEM reflex and signal crossover; and (2) combined analysis of DPOAE level and phase changes warrants further investigations to overcome the difficulty in separating the effects of MOC efferents and MEM contraction. The results also imply that OAE measurement has the potential for being used to investigate the effect of the MEM reflex on sound transmission.

Keywords: Distortion product otoacoustic emission; DPOAE contralateral suppression; Medial olivocochlear bundle; Middle-ear muscle; Acoustic reflex; Contralateral acoustic stimulation

1. Introduction

Evoked otoacoustic emissions (OAEs) are low-intensity acoustic signals emanating from the cochlea in response to sound stimulation and recordable in the ear canal (Kemp, 1978). One type of OAEs is distortion product otoacoustic emissions (DPOAEs), which are recorded when stimulated with two tones at frequencies f_1 and f_2 (where $f_1 < f_2$). It is generally accepted that the production of OAEs is an indication of the active, nonlinear biomechanical property of a normal cochlea. Specifically, it is mainly related to the function of the outer hair cells in the cochlea. By virtue of its non-invasiveness, the OAE measurement has been developed as a tool for evaluating the functional status of the cochlea in laboratory and clinical applications.

The amplitude of OAEs recorded from one ear can be altered by sounds presented, even at a low intensity, in the opposite ear. This is known as sound-induced OAE contralateral suppression, because OAE amplitudes were reduced in most cases (e.g., Mott et al., 1989; Collet et al., 1990; Berlin et al., 1993; Moulin et al., 1993). The OAE contralateral suppression is the consequence of a feedback or control mechanism of the auditory system. Previous investigations have suggested that this reflex phenomenon is mediated by the auditory efferent neurons in the olivocochlear (OC) bundle (e.g., Puel and Rebillard, 1990; Kujawa et al., 1993; Liberman et al., 1996). The OC efferent neurons originate from the superior olivary complex of the brainstem; their nerve fibers project to the cochlea (for review, see Warr, 1992). The nerve fibers in the medial part of the OC system directly innervate the outer hair cells of the cochlea (Guinan et al., 1983), which is the widely accepted origin of OAEs. The medial OC

* Tel.: +1 316 978 6160; fax: +1 316 978 3291.
E-mail address: xiao-ming.sun@wichita.edu

0378-5955/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.heares.2007.12.004

(MOC) system plays a critical role in the OAE contralateral suppression. Hence, the suppression is attributed to the MOC reflex.

The measurement of OAE contralateral suppression has the potential to be a tool for evaluating the function of the auditory efferent system in humans. It has inspired intensive studies (for review, see Hood, 2007; Velenovsky and Glattke, 2007). The technique, however, has not been widely applied in clinical application, partially because the magnitude of suppression is too small (up to a few dB) in most human ears. In previous studies on OAE contralateral suppression, researchers always cautiously chose the suppressor with low-intensity levels to avoid activating another feedback or control mechanism of the auditory system, the middle-ear muscle (MEM) reflex. Several researchers have addressed concern that OAE contralateral suppression includes contribution of the MEM reflex (e.g., Veuillet et al., 1991; Whitehead et al., 1991; Berlin et al., 1993; Burns et al., 1993).

The MEM reflex in an ear can be activated by presenting relatively intense sound stimulation in the opposite ear (for review, see Silman, 1984). It is generally assumed that only the stapedius muscle in the middle ear is involved in this acoustic reflex in humans, which is mediated by the facial nerve. The consequence of the stapedius muscle contraction is a stiffened middle ear, causing an increase in acoustic impedance of the system. A conventional technique for monitoring the MEM reflex has been applied in clinical applications for evaluating the function of the facial nerve, auditory nerve, and middle ear, known as the acoustic reflex test. As the MEM reflex is activated, the stiffened conductive mechanism reduces the transmission of acoustic energy through the middle ear. As a result, the amplitude of OAEs is reduced, as measured in the ear canal in humans.

The MEM reflex shares with the MOC reflex the same afferent neural pathway, i.e., the auditory nerve (Liberman and Guinan, 1998). Both reflexes can be activated by contralateral acoustic stimulation (CAS) and cause reduction of OAE amplitude. It is conceivable that OAE contralateral suppression, commonly attributed to the MOC reflex, includes the involvement of the MEM reflex. To obtain reliable assessment of the OC efferent system using OAE contralateral suppression measurement, any confounding effect of the MEM reflex has to be identified. In one respect, effects of the MEM and MOC reflexes needs to be discriminated so that we are confident in determining the intensity level of the suppressor for eliciting the MOC reflex. In another respect, the extent to which the MEM reflex diminishes sound transmission needs to be estimated so that we may apply the suppressor at higher levels for eliciting the MOC reflex to achieve larger DPOAE change, but with a minimal effect of the MEM reflex. Unfortunately, systematic investigation has been scarce. In pioneering work in this field, Büki et al. (2000) observed the effects of contralateral noise at a low and a high level on DPOAEs for frequencies between 0.5 and 4 kHz. The results revealed evident differences between the changes in both DPOAE level and phase and led to a suggestion that vector analysis of OAEs might be helpful in separating MOC and MEM reflexes. However, large intersubject variance obscured statistical significance of the data. Additionally, their conclusion that the mechanical effect of the stapedius muscle is unlikely to be different at high vs. low levels seems to be inappropriate since it was made on the basis of results from the tests with contralateral sound at only two levels.

In the present study, the level and phase changes of DPOAEs were measured for the stimulus frequencies from 1 to 8 kHz in the presence of contralateral noise at five levels—below, equal to, and above the MEM reflex threshold. The goal of this study was to characterize the DPOAE change by CAS of low and high levels, which may be associated with the MOC and MEM reflexes. The secondary goal was to explore the possibility of applying OAE measurement in assessing the effect of the MEM reflex on transmission of acoustic energy. Results of a preliminary observation were presented at a conference (Sun et al., 2002) but are not included in this report.

2. Materials and methods

2.1. Subjects

A total of 26 adult subjects were recruited for this study. All subjects were females between the ages of 20 and 25 years, except for one 40-year-old male subject. They reported no history of auditory pathology and demonstrated normal middle-ear function as assessed by otoscopy and tympanometry (a peak pressure of ± 25 daPa in tympanogram). Their hearing sensitivity was normal, defined as hearing thresholds of 20 dB HL or better at octave frequencies from 0.5 to 8 kHz in pure-tone audiometry. The study was approved by the Institutional Review Board of the university. All subjects signed a consent form as volunteer participants.

2.2. Apparatus and procedure

A Madsen Zodiac 901 Middle-Ear Analyzer (GN Otometrics, Denmark) was used to measure the tympanogram and the contralateral acoustic reflex threshold (ART) to broadband noise (BBN) in both ears of the subjects. The default probe tone (226 Hz at 85 dB SPL) was employed. White noise was used as the contralateral acoustic reflex activator, and its level varied by 5 dB in increasing steps. The ART, defined as the lowest noise level that produces a measurable change in acoustic admittance, was automatically determined by the system. The ART was employed as a reference in determining the level of BBN presented in the non-test ear in the experiment (see below for details).

With an ILO96 DPT OAE System (Otodynamics Ltd.), the $2f_1 - f_2$ DPOAE was measured for the f_2 frequencies of 1, 2, 4, and 8 kHz in both ears of each subject. The stimulus tones were presented through the earphones with $f_2/f_1 = 1.2$. The levels of the stimuli were $L_1 = 65$ and