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Research Paper

Posture systematically alters ear-canal reflectance and DPOAE properties

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A B S T R A C T

Several studies have demonstrated that the auditory system is sensitive to changes in posture, presumably through changes in intracranial pressure (ICP) that in turn alter the intracochlear pressure, which affects the stiffness of the middle-ear system. This observation has led to efforts to develop an ear-canal based noninvasive diagnostic measure for monitoring ICP, which is currently monitored invasively via access through the skull or spine. Here, we demonstrate the effects of postural changes, and presumably ICP changes, on distortion product otoacoustic emissions (DPOAE) magnitude, DPOAE angle, and power reflectance. Measurements were made on 12 normal-hearing subjects in two postural positions: upright at 90° and tilted at −45° to the horizontal. Measurements on each subject were repeated five times across five separate measurement sessions. All three measures showed significant changes ($p < 0.001$) between upright and tilted for frequencies between 500 and 2000 Hz, and DPOAE angle changes were significant at all measured frequencies (500–4000 Hz). Intra-subject variability, assessed via standard deviations for each subject's multiple measurements, were generally smaller in the upright position relative to the tilted position.

1. Introduction

Noninvasive ear-canal based acoustical measurements have diagnostic potential in the area of neurology to monitor intracranial pressure (ICP) changes. Because the skull is fixed in volume, and its fluid contents are incompressible, changes in cerebral spinal fluid pressure that result from changes in ICP are transmitted to the cochlear fluids. Changes in ICP can be caused by a number of factors, including, head injury, stroke, hydrocephalus, and brain surgery and can lead to worsening brain injury or death by compressing blood vessels supplying the brain or vital brain structures themselves. Current tools used to evaluate ICP objectively (e.g., epidural transducers or intraventricular catheters) are invasive and require direct entry of a probe system through the skull or spine, introducing risks that include infection, intracerebral hemorrhage, and direct brain injury (e.g., Kanter et al., 1985; Manniker et al., 2006; Wolfe and Torbey, 2009; Scheithauer et al., 2009). A noninvasive method for monitoring ICP could eliminate these risks for some patients.

Intracranial pressure changes systematically with postural position (e.g., Chapman et al., 1990). Thus, changing postural position provides a method to induce changes in ICP and study the effects. To this end, it is widely documented that posture affects auditory function, including thresholds, otoacoustic emissions, and middle-ear impedance (for a thorough review see Büki et al., 2000). Thus, the connection between posture and ICP provides a mechanism to study how changes in ICP affect auditory responses and how this relationship might be harnessed to provide a noninvasive means to monitor ICP in some patients.

Wilson (1980) first showed that posture influences otoacoustic emissions, and with this report suggested that the changes might be due to changes in the stiffness of the annular ligament. More recently, a series of publications of both measurements and models from Büki and colleagues demonstrate that low-frequency changes in auditory function with posture are largely a result of changes in middle-ear transmission that result from the changes in ICP associated with changes in posture (Büki et al., 1996, 2000, 2002; de Kleine et al., 2000, 2001). Their measurements and models are generally consistent with the following hypothesis. The auditory

Abbreviations: DPOAE, distortion product otoacoustic emissions; ICP, intracranial pressure; TPP, tympanic peak pressure; MEP, middle-ear pressure

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system is sensitive to changes in ICP because the cochlear aqueduct connects the cerebral spinal fluid to the cochlear fluid; increases in ICP are transferred to increases in intracochlear pressure, which results in outward static displacements of the compliant oval and round windows. These ICP increases are most likely to be detected as reductions in middle-ear transmission that result from an increased stiffness of the annular ligament, which connects the stapes to the oval window (Büki et al., 2000, 2002; Voss et al., 2006), with the effects of increased stiffness most prominent at frequencies below the middle ear's resonant frequency (i.e., below about 2000 Hz).

Theoretically, different middle-ear transmission measurements could be used to detect ICP changes, including otoacoustic emissions (Büki et al., 1996, 2000, 2002; de Kleine et al., 2000, 2001; Frank et al., 2000; Voss et al., 2006), the cochlear-microphonic potential (Büki et al., 2009), changes in middle-ear impedance (Magnano et al., 1994; Liau, 1999), and other related quantities such as reflectance, and changes in displacement patterns of the tympanic membrane (Marchbanks, 1984), which were later shown to be too variable to monitor ICP (Rosingh et al., 1998; Shimbles et al., 2005). An advantage of evoked otoacoustic emissions is that they are affected by two reductions in middle-ear transmission: one in the forward direction as the stimulus and one in the reverse direction as the emission (Voss and Shera, 2004); a limitation is that the emissions may be weak or absent in individuals with a hearing loss. Thus, the potential for monitoring changes in ICP through concomitant changes in middle-ear transmission should be evaluated using multiple measures, and here we quantify how both distortion product otoacoustic emissions (DPOAEs) and reflectance, which is related to impedance measures (e.g., Keefe et al., 1993; Voss and Allen, 1994), are affected by changes in posture, and presumably ICP changes.

The specific goal of this paper is to present measurements of both DPOAE magnitudes and angles and also power reflectance made at the same time at two extreme postures, presumably resulting in ICP changes. Additionally, these measurements were made multiple times on a given subject so that intra-subject variability of these measures could be assessed.

2. Materials and methods

2.1. Overview

Measurements of DPOAE magnitudes, DPOAE angles, and power reflectance were made to characterize how posture, and presumably intracranial pressure (ICP), affects these three measures. Measurements were made in the supine (upright) position and a position with the subject tilted at -45° relative to the horizontal. Additionally, the intra-subject variability for all three measures is quantified through repeated measurements across five sessions.

2.2. Human subjects

Measurements are reported from the left ears of 12 normal-hearing healthy subjects (11 females and one male), ages 19–42 years, all with a negative history for middle-ear problems, hearing thresholds below 20 dB HL at 500, 1000, 2000, and 4000 Hz, and normal tympanograms. All measurements were made between January 2008 and June 2008. Eight additional subjects were recruited but did not complete five measurement sessions because of the time required or discomfort with being tilted at -45°. Subjects were given an otoscopic examination to ensure no excessive ear wax was present in the ear canal. The measurements were approved by the Smith College Institutional Review Board, and informed consent was obtained from all subjects.

2.3. Acoustic measurement equipment

DPOAE magnitudes and angles and reflectance measurements were made with an Etymotic ER-10c probe using software and hardware developed by Mimosa Acoustics (HearID v4.0.13). To maximize the DPOAE magnitude response at the frequency $f_{dp} = 2f_1 - f_2$ at the lower frequencies, we fixed $f_2/f_1 = 1.25$ and $L_1 = L_2 = 75$ dB SPL; DPOAEs were measured at 13 log-spaced frequencies with f_{dp} approximately 500–4000 Hz. Response magnitudes were obtained from the discrete Fourier transform of the time-domain average of N responses. The number of responses N varied with noise level, with a maximum $N = 420$. The artifact rejection algorithm with HearID dropped noisy buffers from the averaging; averaging was stopped when the signal-to-noise ratio at the frequency f_{dp} exceeded 15 dB (or when, the total number of response buffers contributing to the average equaled 420, whichever came first). The noise floor was estimated from a narrow frequency band surrounding the response measured at f_{dp}, and data that fell less than 6 dB above the estimated noise floor were eliminated (Roede et al., 1993). Reflectance and impedance quantities were calculated, as described in the HearID users manual or in Voss and Allen (1994), from pressure measurements made in the ear canal at a level of 75 dB SPL across a broad-band frequency range. Briefly, pressure reflectance R is calculated directly from the impedance, and the pressure reflectance is the complex ratio between the reflected pressure and the incident pressure. The power reflectance $\mathscr{R}$ is the square of the magnitude of the pressure reflectance such that $\mathscr{R} = |R|^2$, and the power reflectance can be interpreted as the fraction of power reflected in the ear canal and at the tympanic membrane.

2.4. Measurement protocol

All measurements were made in a double-walled sound-proof audiometric booth. Subjects were placed on a tilting table (Hang-ups® II Inversion Table) at two postural positions: upright (90° relative to the horizontal) and tilted (-45° relative to the horizontal). The estimated ICPs of the subjects at these two positions are 0 mmHg at 90° and 22 mmHg (about 30 cm H_2O or 293 daPa) at -45° (Chapman et al., 1990; de Kleine et al., 2000; Voss et al., 2006), with some variation from the mean estimates expected. Each subject participated in a total of five measurement sessions across five different days; the duration of time between the first and fifth measurement session ranged from 5 to 34 days, and the time of day which measurements occurred was not controlled. During each session, measurements of DPOAEs and reflectance were made first in the left ear at both upright and tilted positions and second in the right ear at both upright and tilted positions. For each ear, measurements were made in the following order. First, the subject was placed on the tilt table in the upright position. Tympanometry (Earscan, Micro Audiometrics Corp., ES-T) at 226 Hz was used to monitor middle-ear pressure MEP (assumed equal to the tympanic peak pressure TPP). In order to maintain the MEP as close to zero as possible, the subject was asked to swallow; in cases where MEP differed by more than ± 25 daPa from zero, subjects were encouraged to continue swallowing until either the MEP was within ± 25 daPa of zero or the subject demonstrated an inability to equalize his or her MEP near zero. Once the MEP was documented and as close to zero as possible, the ER-10c's foam plug was placed in the ear canal and consecutive measurements of DPOAEs and reflectance were made. Next, the subject was tilted to the -45° position. After tilting, emission measurements reach stability (presumably a stable ICP) within 30 s (de Kleine et al., 2000), so subjects were tilted for 1 min before additional measurements were made. At this position, the MEP sequence described above was repeated, and followed by measurements of DPOAEs