Posture-Driven Intracranial Pressure Changes Revealed by Otoacoustic Emissions: Toward Noninvasive Monitoring in Microgravity

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It is well established that middle ear transmission is influenced by posture. This phenomenon is associated with variations in intracranial pressure (ICP) when a subject transitions from an upright to a supine position. Typically, this transition leads to an increase in ICP. The resulting rise in endocranial fluid pressure alters middle ear (ME) impedance, generally producing an increase in stiffness, which is linked to the imaginary component of the impedance. These impedance variations also affect distortion product otoacoustic emission (DPOAE) phase. This study is aimed at optimizing joint OAE- an ME-based techniques to assess ICP increases under microgravity conditions. DPOAEs were recorded in both upright and supine positions. Additionally, ME energy reflectance, along with the real and imaginary components of impedance, was measured. Typically, the results align with theoretical expectations, but several counterexamples are observed, which need explanation to enhance the diagnostic power of the proposed technique. Overall, joint OAE-based and ME-based ICP estimation demonstrate potential as a benchmark technique for monitoring intracranial pressure changes in space environments, where such non-invasive and reliable physiological monitoring is essential during prolonged missions in microgravity conditions. Further investigations are needed to refine methodological accuracy and broaden clinical applicability across diverse populations and conditions.

Keywords: *otoacoustic emissions, intracranial pressure, middle ear transmission.*

1. Introduction

The accurate non-invasive estimation of intracranial pressure (ICP) is one of the major goals in the field of astronaut health monitoring. During prolonged exposure to microgravity, the absence of the hydrostatic pressure gradient causes a cephalad redistribution of blood and cerebrospinal fluids [1],[2],[3]. The hypothesized ICP increase in prolonged microgravity is considered one of the main health risks for astronauts and is assumed to contribute to the development of the Spaceflight-Associated Neuro-ocular Syndrome (SANS), previously known as Visual Impairment/Intracranial Pressure (VIIP) syndrome. SANS, reported in several astronauts after long-duration missions aboard the International Space Station (ISS), includes vision impairment, optic disc edema, globe flattening, retinal changes, and hyperopic refractive shifts [2], [3]. Since direct ICP measurements by lumbar puncture are invasive and cannot be performed during spaceflight, reliable non-invasive techniques are required to monitor ICP aboard the ISS [4].

Several non-invasive approaches have been proposed for ICP estimation, exploiting indirect physiological markers related to intracranial dynamics [5]. These methods include ophthalmic techniques, such as optic nerve sheath diameter (ONSD) measurement and optical coherence tomography (OCT), fluid-dynamic approaches based on transcranial Doppler ultrasonography (TCD), magnetic resonance imaging (MRI), and near-infrared spectroscopy (NIRS), as well as electrophysiological and acoustic methods [6], [7], [8]. Although these techniques provide valuable information and some have shown promising correlations with invasive ICP measurements, many remain limited by issues such as lack of continuous monitoring capability, dependence on specialized equipment, operator variability, or insufficient accuracy for routine clinical applications [6],[9]. Therefore, compact, continuous, and reliable methods suitable for operational environments such as spaceflight are still needed [5].

Otoacoustic emissions (OAEs) have already been used for this task [3], [4]. with promising results. The OAE-based method relies on the experimentally demonstrated correlation between OAE phase and ICP [10], which is explained by the presence of a direct connection, the cochlear aqueduct, between the cerebrospinal and intracochlear fluids. An increase in ICP therefore increases the DC pressure acting on the middle ear (ME), increasing its stiffness [11], [10]. This stiffness increase produces a measurable increase in the phase of the OAE response recorded in the ear canal. Distortion-product OAEs (DPOAEs) have proven to be especially effective [4]. The use of advanced time-frequency filtering techniques based on wavelet [12], [13] allows the selective extraction of the DPOAE distortion (generator) component, whose phase is intrinsically independent of frequency because of cochlear scale invariance, while significantly improving the signal-to-noise ratio. The filtered component phase difference can be unambiguously averaged over a wide frequency range (a few kHz), providing a sensitive indicator of small ICP changes.

State-of-the-art DPOAE acquisition techniques also involve calibration of the forward pressure of the stimuli. To perform this calibration, preliminary estimates of the Thevenin pressure and impedance of the sound sources must be obtained. As a byproduct, a direct estimate of the middle ear acoustic impedance is obtained. Since middle ear stiffness is also affected by ICP, this quantity gives complementary information. However, the mathematical computation required to get the ME acoustic impedance involves computing ratios of difference between complex quantities, hence significant error propagation issues may easily yield large systematic and random errors. Nevertheless, analyzing the correlation between the two sets of measurements (DPOAE and ME) may allow one to detect anomalies in the acquisition system or and eventually strengthen the statistical power of each diagnostic technique.

In this study, both techniques were applied to a sample of 18 ears from healthy adult subjects. ICP changes were induced by a controlled postural transition from the seated to the supine position. This postural change typically increases the ICP by 5-10 mmHg [14], [3], [4], which corresponds to a DPOAE phase change between 14 and 28°, according to the calibration provided by Avan [10] who measured both ICP and DPOAE phase in patients undergoing controlled ICP increase during neurosurgery. The results are discussed in the light of possible applications to monitoring the astronauts' health and the risk factors they are exposed to in prolonged microgravity environments, such as the ISS, the foreseen Moon-orbiting station and the future spacecrafts dedicated to the exploration of the Solar system.

2. Methods

Eighteen ears of healthy adult subjects were tested in seated and supine posture, using the Titan (Interacoustics, Denmark) system. Swept-sine stimuli (Chirps) of level L1, L2 = 65, 55 dB at frequencies f1(t) and f2(t) were used to elicit the cochlear cubic DPOAE response at fDP(t)=2f1-f2. Least-square fit (LSF) analysis was used to extract the DPOAE signal, and wavelet-based analysis was used to filter the signal in the time-frequency domain to optimally select the wave-fixed distortion component of approximately null phase-gradient delay. The middle ear impedance (and the associated energy reflectance function) was independently measured immediately before the start of each DPOAE acquisition (therefore, with the probe in the same position inside the ear canal).

A data selection criterion based on the SNR of the filtered data was applied to the DPOAE data, while the impedance data, thanks to the much higher levels of the signal, needed no selection.

3. Results

Figure 1 shows an example of the DPOAE phase change associated with the postural transition in one of the examined ears. The phase change is positive, as expected, over most of the examined frequency range.

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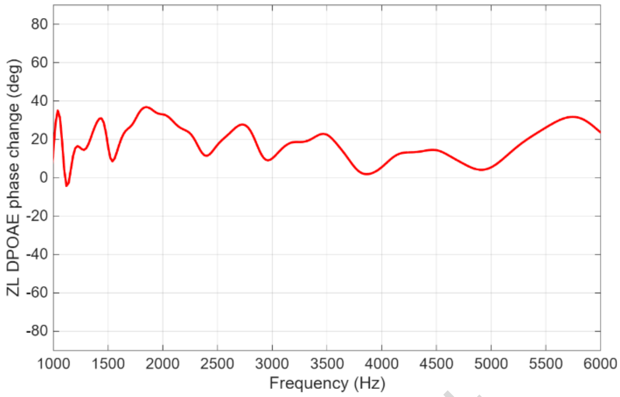

Figure 1. DPOAE phase change associated with the postural change from seated to supine in one of the examined ears.

Figure 2 shows the DPOAE phase change and the Im(Z) change, averaged, respectively, over the 1–3 kHz and the 1–2 kHz frequency range, for all examined ears. Noisy data correspond to missing points in the plot.

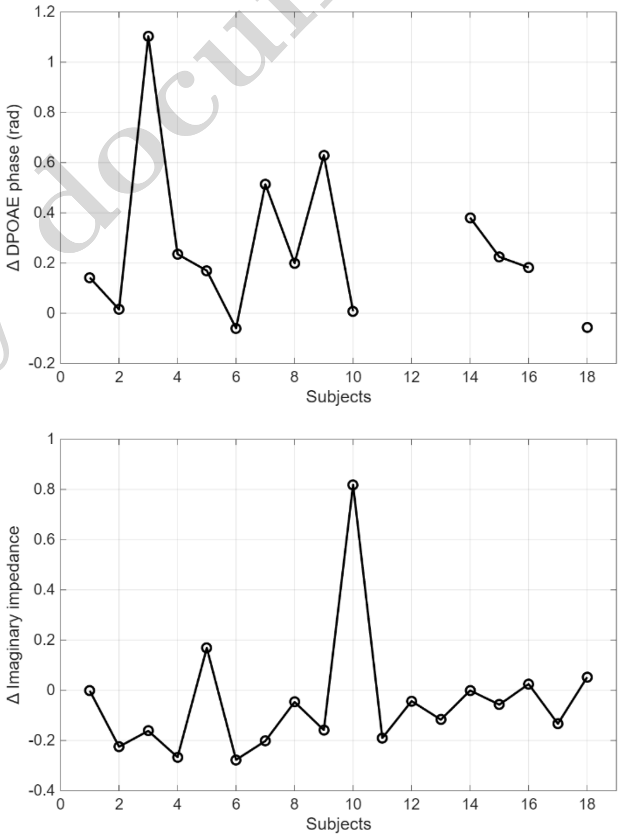

Figure 2. Top: Average (1-3 kHz) DPOAE phase change in all subjects associated with the postural change from seated to supine. Bottom: Same for the imaginary part of the impedance.

The corresponding changes were computed also for the other measured parameters, namely the DPOAE level, the DPOAE phase-gradient delay, the real part of the middle-ear impedance, and the energy reflectance. Different averaging frequency bands are used because the theoretically expected change may have opposite signs in different frequency bands, as shown in Fig.3 for the average change of the imaginary part of the impedance. In this case the average is computed over octave frequency bands, separately for the two postural groups.

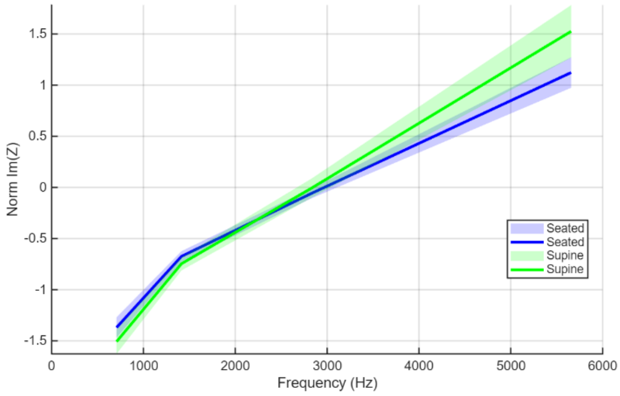

Figure 3. Posture-induced change of the imaginary part of the impedance, averaged over octave bands.

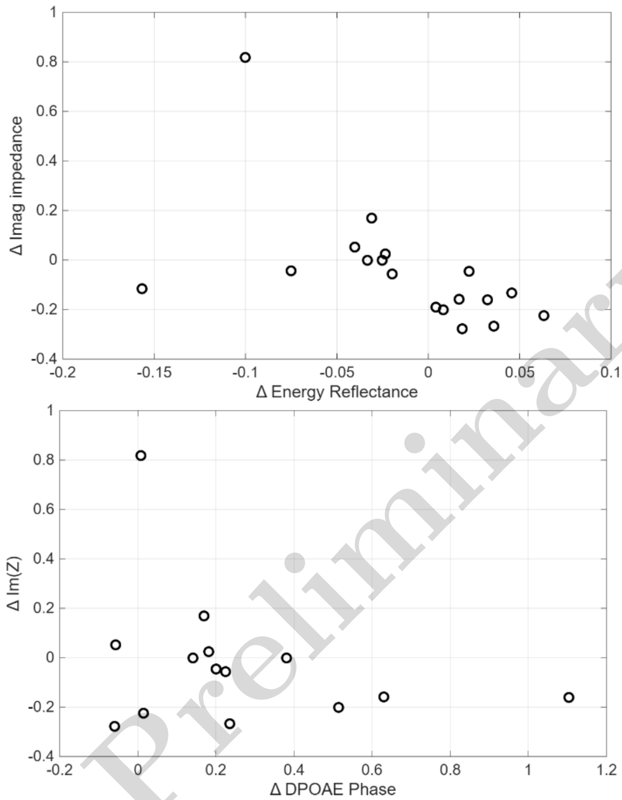

Figure 4. Scatter plots illustrate the correlation between reflectance and Im(Z) changes and between DPOAE phase and Im(Z) changes.

Figure 4 presents scatter plots illustrating the correlation between the posture-induced changes in the ICP-related acoustic indicators. The correlation between Im(Z) and Reflectance changes is high (R = 0.55), which is not surprising considering that the two quantities are not independent, while the correlation between Im(Z) and DPOAE phase changes, which are independently measured, is poorer (R = 0.3).

4. Discussion

The DPOAE phase shows systematically positive differences when subjects transitioned from the seated to the supine posture, consistent with the expected ICP increase associated with cephalad fluid redistribution. This finding agrees with previous studies reporting posture-induced DPOAE phase changes and supports the sensitivity of the DPOAE distortion component to ICP-related changes [10]. [3], [4]. A systematic negative change of Im(Z) in the <2 kHz range, which is expected for a stiffness increase, is also observed. In contrast, the other acoustic observables exhibited less systematic behavior and larger variability across subjects. In all cases, the size of the effect shows a large inter-subject variability, which is mostly attributable to the uncertainty of each indirect method that we used. The limited correlation among different observable quantities suggests that they may be influenced by other different physiological and measurement-related factors rather than reflecting identical aspects of ICP-related changes. Nevertheless, the complementary information provided by these techniques may be useful for improving the robustness of non-invasive ICP assessment and for identifying potential acquisition or calibration anomalies. Although the present study employed posture-induced ICP changes as a terrestrial analogue of the cephalad fluid shifts occurring in microgravity, the results further support the potential of DPOAE-based methods for astronaut health monitoring during long-duration space missions**.**

5. Conclusions

The combined middle ear – DPOAE technique proposed in this study could help the robustness and sensitivity of non-invasive ICP estimation by providing complementary information from two independent acoustic indicators. The combined analysis may help identify systematic errors and strengthen the diagnostic value of each technique while preserving the non-invasive nature of OAE-based methods, without increasing the test time, since middle-ear impedance measurements are an intrinsic part of the forward-pressure-level calibration procedure required for advanced DPOAE acquisition methods.

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