High Altitude Performance of Loudspeakers and Potential Impact on Audiometric Findings

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BACKGROUND: The evaluation of how air rarefaction can affect a loudspeaker performance at altitude implies the need for characterization of earphones during hypobaric conditions. The aim of this study was phonometric analysis at different altitudes of the acoustic output of a widely used earphone model, along with its consequences on audiological investigations conducted under such environmental conditions.

METHODS: The transfer function of a TDH-39P earphone was analyzed with an artificial ear under nine different altitude levels, from sea level up to 35,000 ft, inside a hypobaric chamber. A specific phonometric system not sensitive to environmental pressure changes was used. Other potentially confounding factors, such as environmental temperature and humidity, were continuously monitored.

RESULTS: No relevant temperature or humidity changes were detected. The sound pressure level generated by the earphone under hypobaric conditions was found considerably affected by air density changes. These data produced a correction table aiming at recalibrating the earphone's output at each audiometric octave test frequency within the 250–8000 Hz range. Quite different characteristics of response were observed at different audiometric frequencies. Such findings were particularly evident for altitudes exceeding 12,000 ft.

DISCUSSION: The development of a frequency-selective and altitude-related correction factor for acoustic stimuli is an essential aspect when hearing threshold measurements in hypobaric environments are performed.

KEYWORDS: hypobaric hypoxia, acoustic stimulus, correction factor, hearing, threshold.

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Previous reports from our laboratory analyzed the electrophysiological behavior of the human auditory system during short lasting exposures to hypobaric hypoxia.[9,10,16] In humans exposed to real or simulated (i.e., inside a hypobaric chamber) high altitudes, the auditory system was also investigated by other authors for longer exposures,[2,4,5] to analyze cognitive effects,[7,11,17] or with nonelectrophysiological methods.[3,8] All such reports mainly aimed at analyzing normal individuals during hypoxia with the use of different acoustic stimuli, such as pure tones, clicks, logons, and others. However, under hypobaric conditions, possible variations of the acoustic stimulus should also be considered, since air rarefaction could theoretically affect its correct delivery, with a consequent potential biasing of the audiological findings.

In a recent preliminary investigation from our laboratory, a Telephonics TDH-39P earphone, which is a widely used model for both clinical and research purposes, was tested in a hypobaric chamber at different altitudes using a specific and dedicated recording system.[1,13] With respect to sea-level measurements, the electro-mechano-acoustical components of this earphone exhibited a transfer function that varied with altitude (i.e., with the decrease of air density). Moreover, the peak of its output that characterizes the response at sea level, which is located at about 3250 Hz, showed a progressive shift toward lower frequencies as a consequence of the altitude increase. Therefore, frequency specific changes of the stimulus intensity were observed at different altitudes, often resulting in relevant

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variations of the final sound pressure level (SPL) recorded by the sound level meter.

On the basis of such findings, in this present study a similar experiment was replicated with the specific aim of identifying some practical applications of these results for audiometric testing at different heights above sea level. Therefore, the altitude at which an acoustic stimulus begins to be significantly altered by air rarefaction when using standard clinical earphones (i.e., similar to the TDH-39P) was analyzed. Moreover, a frequency specific analysis of the amount of the stimulus correction factor for each selected altitude was also performed.

A dedicated recording system was then assembled, mainly focusing attention on the standard audiometric octave test frequencies and selecting in a hypobaric chamber a sequence of altitudes that might be helpful for clinical and/or research purposes, on the basis of previous reports, and of those standard simulated heights usually employed in aviation medicine laboratories.[15] An easy-to-read correction table was then developed, aiming at correcting audiological data recorded at different altitudes. Eventually, such a correction criterion was applied on previous literature data,[3] where a similar earphone was used without the concurrent use of a correction procedure, to analyze the potential impact of this procedure on final results.

METHODS

The data of this study were recorded within the hypobaric chamber of the Italian Air Force Flight Experimental Centre, Aerospace Medicine Department (Pratica di Mare AFB). The SPL generated by a TDH-39P earphone (electrical resistance: 10 ohm) is described as an artificial ear configuration. Due to the technical characteristics of this method, possible bias related to some variables potentially affecting the sound propagation, such as the geometrical divergence or the interference on the part of the ground,[12] can be ruled out. For the specific purpose of this research, a calibrated 80 dB SPL white noise stimulus (frequency range: 0–50,000 Hz) was generated by a National Instruments PXIe-1073 mainframe platform equipped with two PXI 4461 boards for 24-bit resolution signal generation and acquisition controlled by a Labview routine running on a personal computer. The acoustic signal was delivered via a TDH-39P earphone, which was coupled to an artificial ear (Bruel & Kjaer type 4153, Copenhagen, Denmark) equipped with a 1/2" microphone with IEC 61,094-4 WS2P Compliance (Gras 40AG), whose frequency range (±1 dB) was 5 to 12,500 Hz and whose open-circuit sensitivity at 250 Hz (±1 dB) was 12.5 mV/Pa. Such a recording setup is substantially insensitive to the environmental pressure changes analyzed in this study, as previously documented by Rasmussen.[13]

The earphone's output was continuously monitored for at least 1 min at each selected altitude, so that an absolutely stable acoustic signal could be recorded and taken into account for data analysis. Ambient pressure variations were obtained within the hypobaric chamber normally used for the aerophysiological training of Italian Air Force aircrew members, keeping constant values of temperature and humidity, due to their potential influence on sound transmission parameters.[6,12]

The recordings were first performed at sea level and then at the following simulated altitudes: 9000; 12,000; 15,000; 18,000; 20,000; 25,000; 30,000; and 35,000 ft (2743, 3658, 4572, 5486, 6096, 7620, 9144, and 10,668 m). Such environmental pressure levels were selected according to those used in previous studies involving the auditory system under hypobaric hypoxia; moreover, the simulated altitudes normally adopted in many laboratories to perform a standard aerophysiological training were also examined.

The difference between the SPL recorded at each selected altitude with respect to the one observed at sea level was analyzed. In particular, for each audiometric octave test frequency, a correction table was developed, and was also used for a review of previous literature data[3] to evaluate how the use of this method can modify the final findings.

RESULTS

No relevant temperature or humidity changes were observed throughout the data collection. Therefore, the following findings could be attributed to the sole ambient pressure variations.

Fig. 1 shows in a 3D graph the SPL (in dB) recorded from our artificial ear coupled with the TDH-39P earphone at the different altitudes analyzed. As shown in the figure, the SPL exhibited various frequency/altitude specific changes, which were in part due to the shift of the resonance peak toward the lower audiometric frequencies. In our data collection, at sea level, such a peak was recorded at 3252 Hz, and progressively shifted toward lower frequencies as altitude increased, reaching 1975 Hz at 35,000 ft.

More details on such frequency related changes are shown in **Fig. 2**, where the responses obtained at different altitudes are reported within the 500–4500 Hz frequency range. In this figure, the progressive shift of the resonance peak toward lower frequencies is very evident, along with the altitude-related SPL reduction at low and high frequencies, where high intensity changes (about 10 dB in some cases) were detected.

However, within the 1000–3000 Hz frequency band, the response showed an irregular behavior, with the recording of higher SPLs at higher heights, due to the evident shift of the resonance peak from 3252 Hz at sea level toward lower frequencies as altitude increased. This was particularly evident at 2000 Hz, where the SPL systematically increased from sea level, having an opposite behavior with respect to the theoretically expected one (Fig. 1 and Fig. 2).

The double cross of the response curves recorded at different altitudes (within the 1000–1500 Hz frequency band and between 2000 and 3000 Hz, as shown in Fig. 2) was also

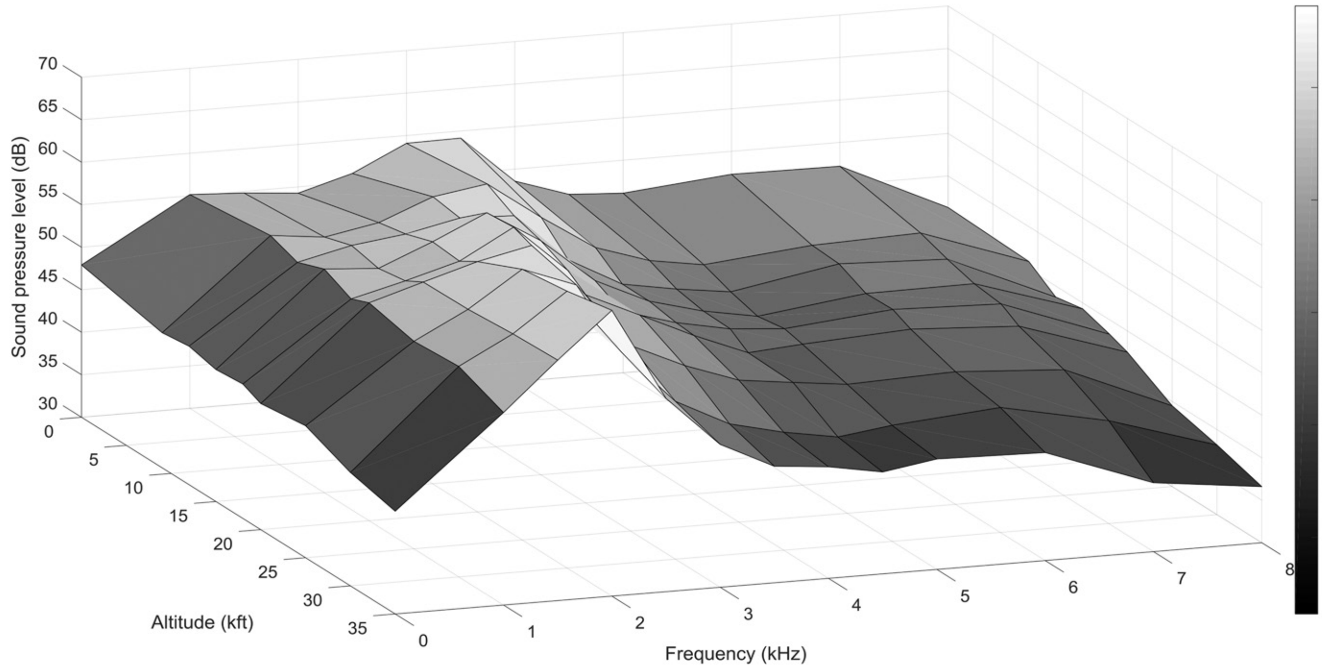

Fig. 1. 3D representation of the SPL recorded at different frequencies within the altitude range analyzed in this study.

responsible for the very irregular direction of the intensity parameter at some frequencies. Such irregularities were particularly high above 2000 Hz, where higher and lower stimulus intensities alternated across consecutive altitudes (Fig. 1 and Fig. 2), as in the case of 2500 Hz, where the SPL increased according to the following sequence: 35,000; 30,000; sea level; 9000; 12,000; 25,000; 20,000; 15,000; 18,000 ft.

For a practical utilization of these findings for audiometric purposes, the results are also summarized in **Table I**, where the correction parameters (in dB) with respect to sea level recordings are indicated for each audiometric octave test frequency for all the altitudes that were analyzed. Finally, an example of how neglecting the stimulus correction can alter audiometric data is reported in **Fig. 3**, where the original findings from Burkett and Perrin,[3] who did not report applying any correction method, are shown, along with the changes in their findings according to the parameters of Table I.

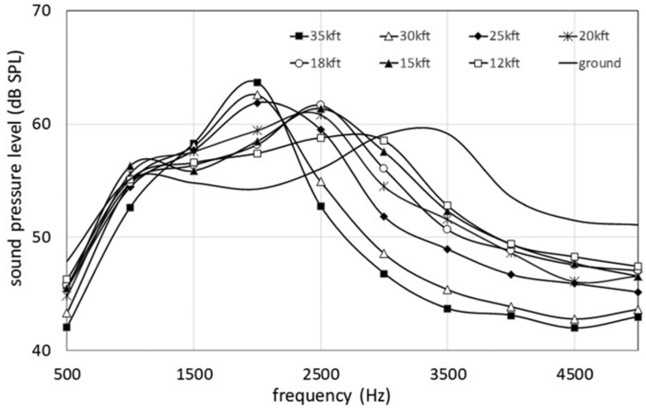

Fig. 2. SPL curves recorded at different altitudes analyzed in this study.

DISCUSSION

Various audiological findings were reported in humans at high altitudes, where different tests were performed using several forms of acoustic stimuli. In most cases, the main purpose was the analysis of the effects of hypobaric hypoxia on the human auditory system, that in many reports resulted in different degrees of impairment during hypoxia, including the cognitive response following acoustic stimulation. The small changes frequently observed during acute exposures to hypobaric hypoxia for the audiometric threshold and the acoustic pathways electrical response emphasize the need for a correct stimulus calibration at altitude to arrive at comparable experimental conditions between sea level recordings and those obtained under hypobarism.

Our findings indicate how the intuitive concept of a reduced sound intensity due to air rarefaction can be supported by objective data, which also clearly point out the presence of

Table I. Final Audiometric Octave Test Frequency Corrections Needed (in dB) to Adapt Pure Tone Audiometry Findings at the Different Altitudes (in ft) Analyzed in This Study with Respect to Sea Level Recordings.

	FREQUENCY					
ALTITUDE	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Sea level	0	0	0	0	0	0
9000	3.2	2.0	−1.1	−2.5	1.9	0.4
12,000	3.2	1.6	0	−3.1	4.2	2.6
15,000	2.3	2.4	−1.2	−4.2	4.2	1.9
18,000	3.7	2.1	0.4	−3.9	4.7	2.9
20,000	3.5	2.2	0.2	−5.5	5.6	4.8
25,000	3.9	2.4	0.7	−7.6	6.9	6.7
30,000	4.8	4.6	0.4	−8.3	9.7	8.1
35,000	5.8	5.8	2.5	−9.4	10.5	9.7

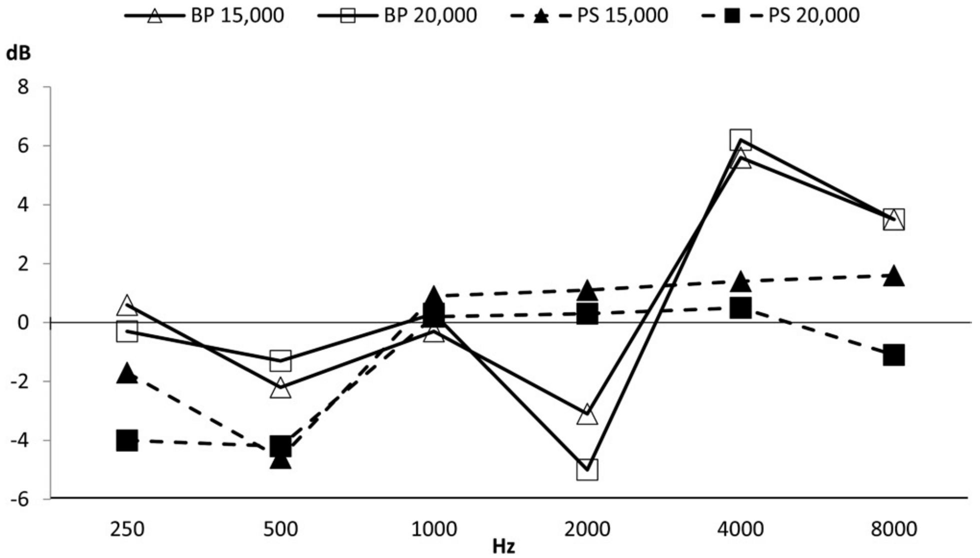

Fig. 3. Difference from sea level recordings between the hearing thresholds reported by Burkett and Perrin (BP) at 15,000 (white triangles) and at 20,000 ft (white squares), without (solid lines) and with the correction factor from the present study (PS: dotted lines, black triangles, and black squares).

important frequency-related variations. In the case of the TDH-39P output, the observed changes are probably related to a different transducer's response when the pressure load applied on the two sides of its membrane is reduced due to ambient air depressurization.[1,13]

Nevertheless, a similar behavior can be predicted for most earphones, due to their technical similarities with the TDH-39P, and deserve more research even for other devices where an electro-mechano-acoustical transduction is performed, as confirmed by preliminary data on hearing aids, where both loudspeakers (i.e., the acoustic output generators) and microphones (i.e., the electric input generators) are used.[14] In these tools, a global decrease of the loudspeaker output of about 3 dB at 15,000 ft was observed, in agreement with the results of the present study. Therefore, a correct stimulus evaluation at least from altitudes exceeding 12,000 ft is certainly needed (see Table I) when the correction parameter at some frequencies approximates the 5-dB step usually adopted by clinical audiometers for intensity sequencing.

The analysis of past literature findings shows that in many cases the adoption of a stimulus correction under hypobarism was not performed. Although an intensity decrease of a few dB, as in the case of the low altitudes usually adopted for research on humans, should play a negligible role when supra-threshold stimuli are delivered, the risk of obtaining biased data increases when auditory threshold detection is the object of the study[3] or when very low intensity signals are recorded, as in the case of otoacoustic emissions.[8]

Fig. 3 shows the results of applying the correction procedure indicated in Table I on the data reported by Burkett and Perrin in 1976, who performed a pure tone audiometric testing at 15,000 and 20,000 ft on eight subjects using a THD-39 earphone.[3] In their study, a significantly better auditory threshold at 2000 Hz was detected at both 15,000 and 20,000 ft at the right ear. However, after correction, a substantially flat audiometric response (i.e., with no changes) can be observed from 1000 to 8000 Hz, with a concurrent mild threshold shift at low frequencies (i.e., 250 and 500 Hz).

The data of the present study confirm those of a preliminary report from our group,[1] where the same type of loudspeaker was characterized under hypobaric conditions using both a free field and an artificial ear setup. However, in the present research, different altitudes were selected based on past literature data, while the analysis was specifically focused on the practical implications in audiological tests, with the consequent use of the sole artificial ear configuration. In conclusion, the different output from earphones must be considered when auditory tests are performed at high altitudes, particularly above 12,000 ft, and a stimulus correction factor must be adopted in such environments, especially when minor audiometric changes are expected.

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