Hearing Aids' Performance in Hypobaric Environments

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OBJECTIVE: High altitudes imply exposure to a decreased ambient air pressure. Such a situation may also alter the performance of acoustic transducers using vibrating diaphragms due to air rarefaction. This study aimed at analyzing the performance at high altitude of hearing aids (HAs) where mechano-electric and electro-mechanic transducers are used.

METHODS: A hypobaric chamber was used to perform two separated experimental sessions. In the first one two commercial models of HAs were exposed to a simulated altitude of 25,000 ft (7620 m) and to a subsequent rapid decompression profile, with a rapid climb (< 3 s) from 8000 (2438 m) to 25,000 ft. The second session separately analyzed the performance of microphone and receiver at an altitude of 9000 and 15,000 ft (2743 and 4572 m). Before and after the first session, the HAs were tested with an electronic ear while a dedicated recording system was used in the second session.

RESULTS: No HA damage or dysfunction was detected during the first session. In the second one, the microphone showed a mild decrease of its output, while the receiver exhibited a much higher reduction of its output.

CONCLUSION: Our findings highlight the safe use of HAs even under extreme environmental pressure changes. For altitudes exceeding 10,000 ft (3048 m), a recalibration of the HA's output via a dedicated program may be suggested.

KEYWORDS: hearing aids, aviation medicine, altitude, pressure, transducer, flight.

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A high prevalence of hearing impairment has been reported by the World Health Organization, indicating 6.1% of the world population (i.e., approximately 466 million people) are affected with disabling hearing loss.[11] This has practical consequences on aviation and high-altitude medicine, since many of these hearing impaired individuals will experience such environments, either as aircrew members or, more frequently, as passengers, sportsmen, or mountaineers. Moreover, in the world a few hundred thousand individuals live at altitudes above 10,000 ft (3048 m), primarily in the Andes and Tibet.[5] As to the aviation environment, the ICAO data from the pre-COVID-19 pandemic document 4.322 billion passengers carried on scheduled services during 2018.[7] Such a huge number of individuals, along with civil and military aircrew members, globally represent a population where hearing disorders should be taken into account, while also aiming at preserving safety parameters and communication. Additionally, more than 40% of leisure passengers and more than 30% of business passengers are 45 yrs or more of age,[14] when a progressively increasing prevalence of hearing impairments can be observed due to the onset of presbycusis and to its summating effects with other chronic audiological disorders, such as noise induced hearing loss, ototoxicity, middle ear diseases, and others. Presbycusis is defined as a hearing loss associated with the ageing process and can be observed from the age of about 40,[3] deserving particular care when flight certifications for aircrew members are issued.[2] In such patients, a significant benefit can be obtained with the use of hearing aids (HAs), whose utilization is very variable across countries.[16] In Italy, an overview indicated a total adoption rate of about 30% among individuals affected with disabling hearing loss,[1] corresponding to 3.6% of the total population (i.e., about 2 million people). Thus, an exposure of several thousands

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of individuals wearing HAs to reduced environmental air pressures, such as those experienced in flight or during skiing and mountaineering, can be easily predicted. From an audiological point of view, a reduced ambient air pressure may also impair human hearing capabilities due to the effects of hypobaric hypoxia, although this can usually be observed at relatively high altitudes.[4,9,15] In general, hypoxia is considered of physiological importance when the altitude exceeds 10,000 ft (i.e., 3048 m).[12] However, even in these cases, a reduction of ambient air pressure of about 30% can be obtained, and this implies a mild form of acute hypoxia, along with a different electromechanical performance of loudspeakers, with potentially negative consequences in the field of speech communication.[8] Such a finding can probably be applied to many electronic devices where an electromechanical and/or a mechano-electrical transduction is performed, as in the case of headphones (normally used in aviation for radio communications) or of HAs. The performance under hypobarism of a TDH-39 headphone was already analyzed in a previous report from our laboratory, documenting evident altitude-related changes.[8] Such findings were presumably due to the effects of the air rarefaction on its vibrating diaphragm when the test altitude was increased. Theoretically, in the case of HAs, this might modify the function of both the in- and output transducer where a diaphragm is located. Therefore, the aim of this investigation was the analysis of the HAs' performance under high altitude conditions, separating the incoming function of the microphone from the outgoing one of the receiver.

METHODS

This research included two separated experimental sessions, the aim of which was an analysis of different aspects in HA performance under high altitude conditions. The first one was dedicated to the analysis of the resistance of two different models of standard commercial HAs under intense and rapid pressure variations, while the second separately analyzed the response of a HA microphone and receiver during exposure to two environmental high altitude situations [i.e., just below the physiological threshold of 10,000 ft and at 15,000 ft (3048 and 4572 m)]. Due to the potential effects of ambient temperature changes on some parameters which were examined in this investigation, this was monitored throughout the exposure to the hypobaric environment. The two different setups used are described below.

Experimental Session 1

Two different types of "behind the ear" HAs (CRAI models Vista TM 312 and TR 312; Bovolenta, Padua, Italy) were tested inside a hypobaric chamber according to the same flight profiles used for the standard aeromedical training of aircrew members[10] at the Aerospace Medicine Department of the Italian Air Force Flight Experimental Centre (Pratica di Mare AFB). The HAs were preliminarily tested with an electronic ear (Natus Otometrics, model Aurical HIT, Taastrup, Denmark), that documented their correct performance. To better simulate actual functioning conditions during hypobarism, the two HAs were provided with their own battery and ear couplers (earhooks and two different models of soft plastic earmolds) and were turned on and placed on a small board positioned on a standard training seat inside the chamber. Thus, from ground level the ambient air pressure was reduced at a rate of 5000 ft $\cdot$ min^{-1} (1524 m $\cdot$ min^{-1}) to a value corresponding to an altitude of 25,000 ft (7620 m) and maintained for about 15 min; thereafter, a descent to ground level was performed at a rate of 4000 ft $\cdot$ min^{-1} (1219 m $\cdot$ min^{-1}). This was followed by a rapid decompression profile, where from a starting altitude of 8000 ft (2438 m) the cabin pressure was suddenly (< 3 s) decreased to an equivalent altitude of 25,000 ft (7620 m), simulating an accidental and rapid decompression of a pressurized cockpit according to the NATO schedule.[10] Throughout these profiles, the two HAs were repeatedly checked by a chamber operator to evaluate on a subjective basis their correct performance. Eventually, the two HAs were again tested with the same electronic ear to detect possible changes in their global performance and I/O parameters.

Experimental Session 2

The aim of this second session was a separate evaluation of both transducers (i.e., microphone and receiver). For this purpose, the same hypobaric chamber from experimental session 1 was used, and two simulated flight profiles were selected with the aim of analyzing the behavior of these two HA components at ambient pressure levels which could theoretically be met by hearing impaired patients at different altitudes. The microphone (Knowles Electronics model EM-23,046-000, Itasca, IL, USA) and the receiver (Knowles Electronics model ED-21,913-000) were separately evaluated and the target altitudes were set at 9000 and 15,000 ft (2743 and 4572 m, respectively). Therefore, this experimental setup included two different recording steps: the first one dedicated to the analysis of the microphone (i.e., the mechano-electrical input transducer), and the second to that of the receiver (i.e., the electro-mechanical output transducer). To perform the first test, a loudspeaker (model TDH-39P, Telephonics, Farmingdale, NY, USA) was positioned in front of the microphone at a distance of 10 cm. The performance of such a loudspeaker was already analyzed in a previous research, so that its output could be calibrated according to the different altitude.[8] The recording system included two parallel microphones: the HA and the reference one (model Bruel & Kjaer 4190, Duluth, GA, USA), whose frequency range (± 1 dB) was 6.3 to 20,000 Hz, and whose open-circuit sensitivity at 250 Hz (± 1.5 dB) was 50 mV/Pa. Its electric input was amplified by a Bruel & Kjaer NEXUS 2690 and then stored on the AI0 acquiring channel, as indicated in **Fig. 1** (top panel). It is important to note that such a reference microphone is not sensitive to the ambient pressure values adopted in this study, as documented by Rasmussen.[13] Thus, the HA microphone performance could be easily compared to that of a recording system insensitive to the two altitude levels used in this experiment. The AI1 channel received the signal from the HA microphone from an adequate amplifier/impedance adapter interface. For this testing, a calibrated 80 dB SPL white noise stimulus (frequency range: 0–50,000 Hz) was

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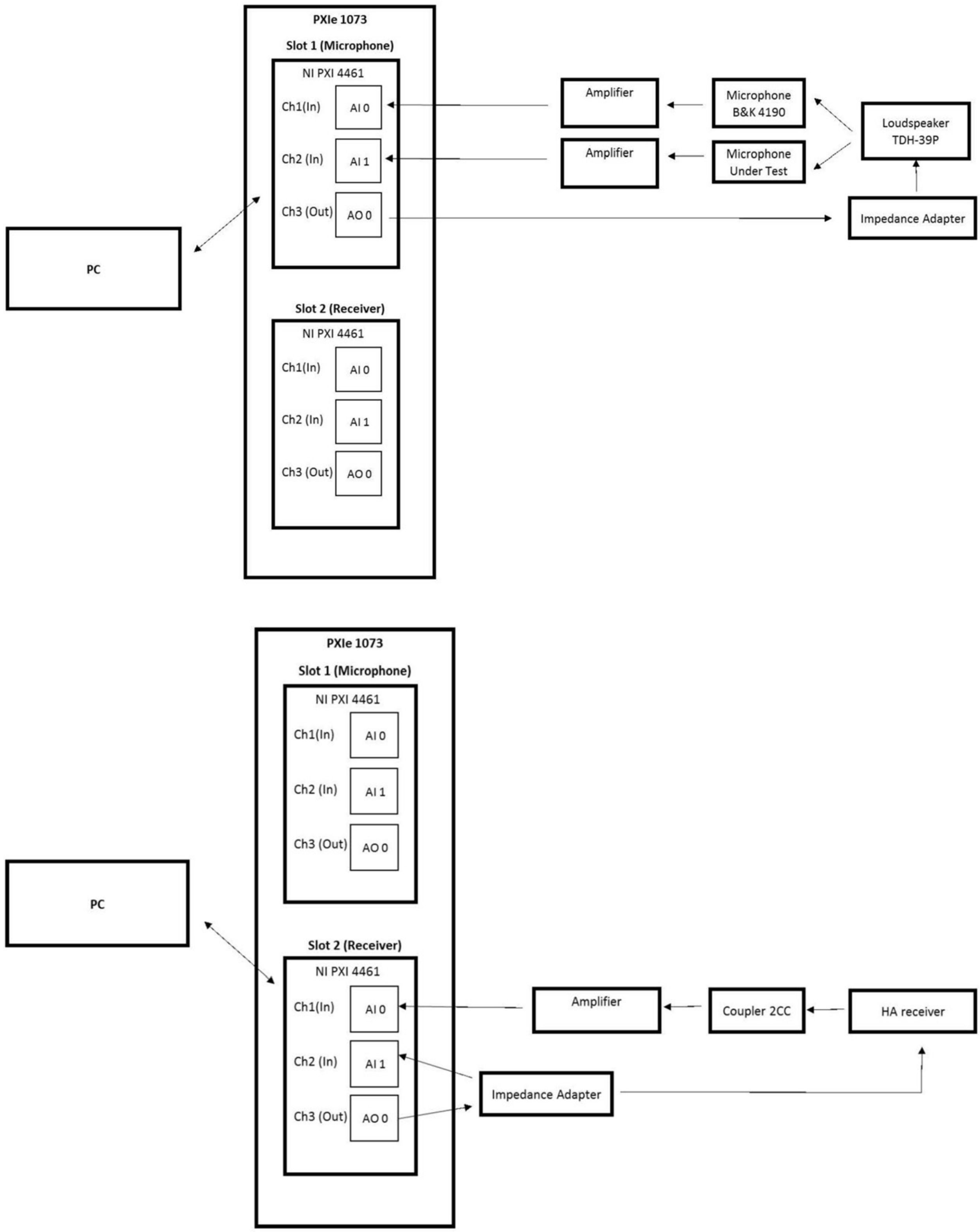

Fig. 1. Schematic representation of the two separated recording channels used for the microphone (top) and the receiver (bottom).

generated by a program written in LabView and delivered via the TDH-39P earphone. The Digital-to-Analogic generation and the Analogic-to-Digital acquisition systems were based upon a National Instruments (Austin, TX, USA) platform, where two NI-PXI 4461 electronic boards were installed on a NI-PXIe 1073 mainframe platform; each board was equipped with two input and two output distribution channels, having a sampling frequency up to 204.8 kHz and a 24-bit resolution on

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generation and acquisition, controlled by a Labview routine running on a personal computer.

In the second step, the HA receiver (i.e., the output transducer) was coupled to the recording system via a 2cc coupler and was stimulated by a 1-V peak to peak electric stimulus, generating pure tone series whose frequency ranged from 100 to 10,000 Hz at 50-Hz intervals. The sampling frequency was set at 40,960 Hz. The acoustic output was captured with the same method adopted in the previous step (i.e., Bruel & Kjaer 4190 microphone and Bruel & Kjaer NEXUS 2690 amplifier) and then stored on the AI0 input channel of the second NI-PXI 4461 electronic board. The schematic configuration setups of both step 1 and 2 are summarized in Fig. 1, top and bottom panels, respectively. The sequence "ground level, 9,000 and 15,000 ft" was adopted to test the two transducers at different altitudes, and the arithmetical average of three recordings from each altitude was taken into account for data analysis.

RESULTS

No relevant temperature changes (i.e., < 2 C°) were detected throughout the two experimental sessions, so the following findings can be substantially attributed solely to the air pressure and volume variations.

Experimental Session 1

During this session, the two HAs did not show any evident dysfunction, at least as far as the subjective criterion adopted by the chamber operator can be taken into account. However, no alteration of their external shape (including battery holder, earhook, and earmold) could be detected on visual inspection during and after both the simulated flight profiles. Thus, no apparent impact due to the air pressure changes during climb and descent could be observed at visual inspection, nor could any altered acoustic output be detected by the chamber operator throughout the test. The lack of evident derangements was confirmed by the electronic ear testing, which exhibited identical I/O curves in the pre- and postexposure recordings. Therefore, the ambient air pressure changes used in this experimental session did not provoke any significant dysfunction, despite the normal presence of small air volumes inside the different HA components.

Experimental Session 2

Fig. 2 and **Fig. 3**, respectively, indicate the global change in microphone and receiver performance at different altitudes, having as a reference point their behavior at sea level (corresponding to the 0 value on the ordinate scale). Minor and relatively uniform changes across frequencies were detected for the microphone (i.e., the generator of the electric input to the HA amplifier), as indicated in Fig. 2. In this case, the mean intensity decrease was about 1 dB at 9000 ft (2743.2 m; dotted line), and 2 dB at 15,000 ft (4572 m; solid line). As shown in the figure, substantially no intensity reductions were detected in the 4000–4500 Hz frequency range. More relevant intensity changes were observed when the receiver was tested (Fig. 3) and a mean output decrease from 0 to about 5 dB (according to the frequency)

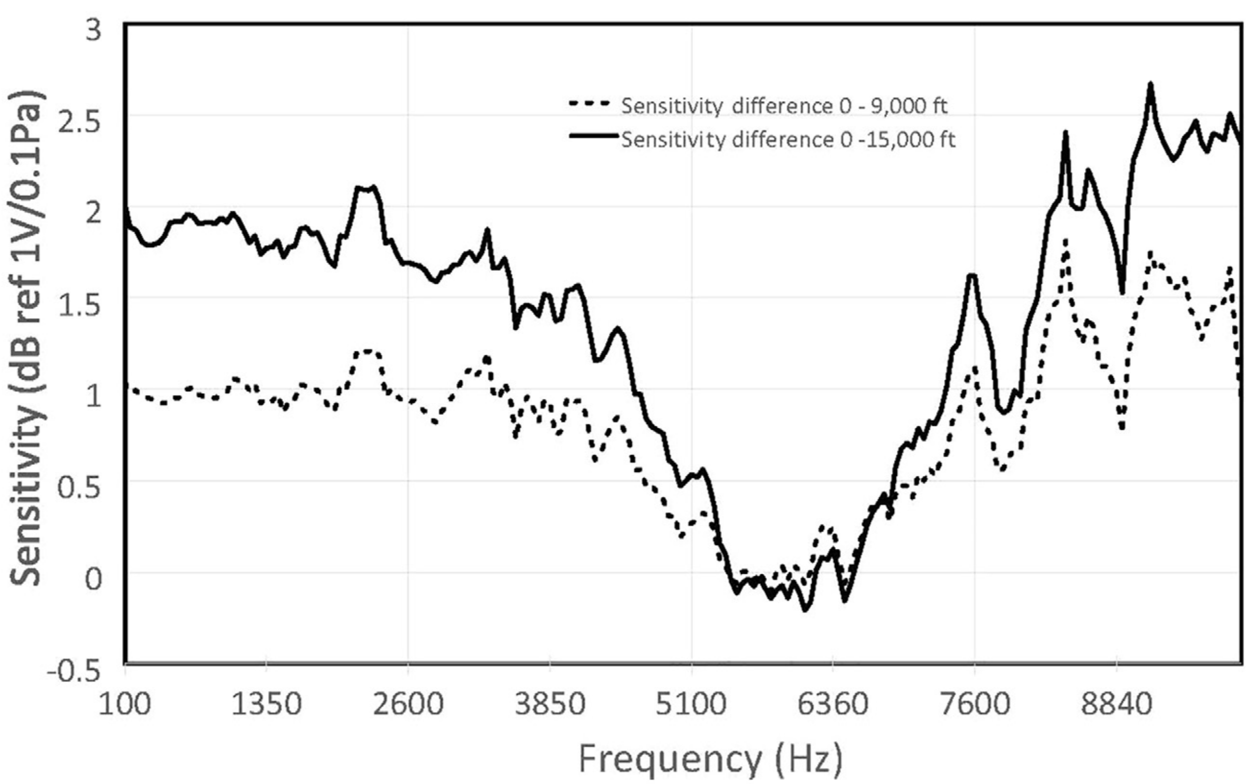

Fig. 2. Microphone's output variations in dB at 9000 (dotted line) and at 15,000 ft (solid line) with respect to the ground level recording.

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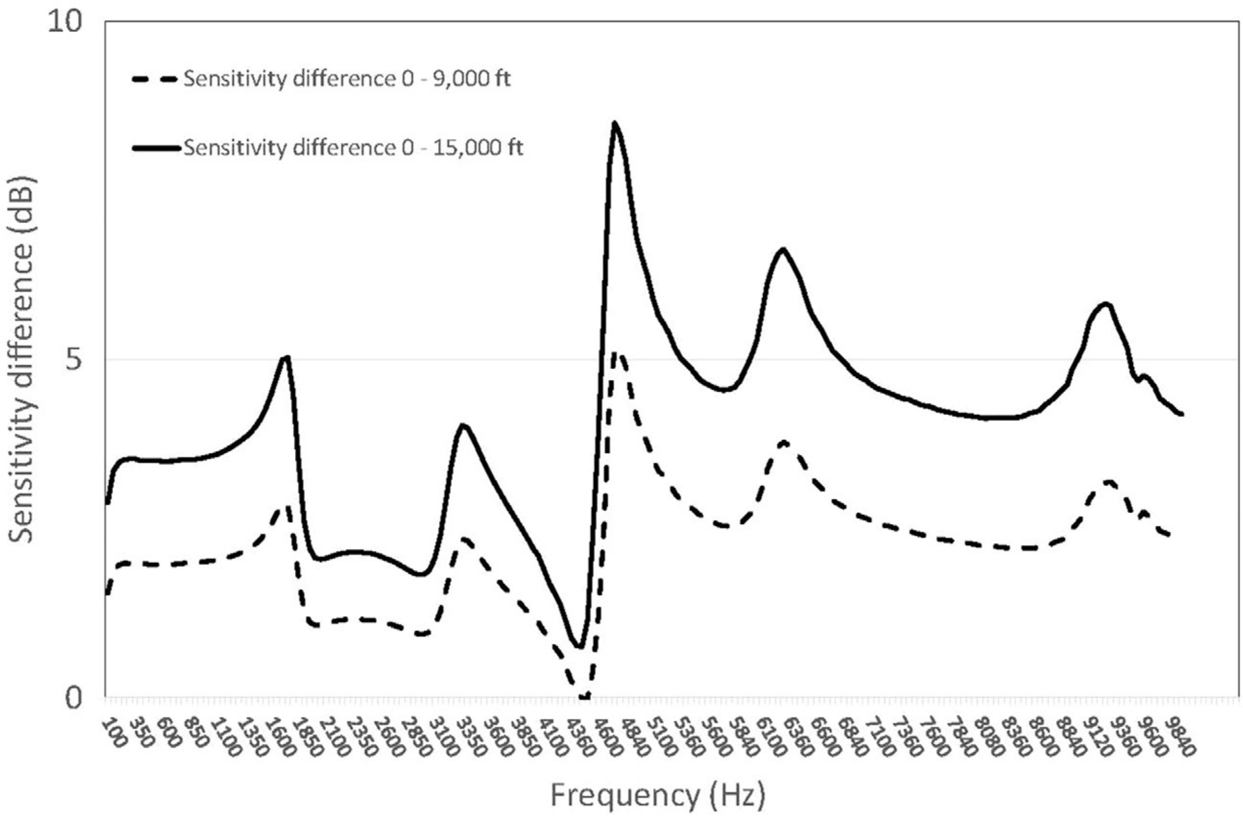

Fig. 3. Receiver's output variations in dB at 9000 (dotted line) and at 15,000 ft (solid line) with respect to the ground level recording.

could be observed at 9000 ft (dotted line), and from 1 to about 9 dB at 15,000 ft (solid line). As shown in Fig. 3, the receiver's performance was quite different across frequencies, with alternating frequency bands differently affected by the environmental pressure changes so that, especially at 15,000 ft, the acoustic output could highly vary.

DISCUSSION

Globally, the two HAs analyzed in this study exhibited a good resistance even if exposed to sudden and intense ambient pressure changes, as documented by the first session of this experiment. Such a finding highlights the possibility of a safe utilization of these devices even under the extremely variable environmental conditions that were simulated in this investigation, at least as far as the construction and technical characteristics of these two HA models is concerned. As expected from our past experience with other electronic transducers,[8] a global and progressive decrease of both the microphone and the receiver output could also be observed when the ambient air pressure was lowered, as documented by the second session of this investigation. Such variations were progressively more evident as the simulated altitude increased, while substantially maintaining the same shape of the output, in agreement with the ambient air rarefaction. The different behavior between the receiver and the microphone, the former being more sensitive to ambient pressure changes, was presumably due to the different technical and construction characteristics of the two types of transducers that were analyzed in this study. This phenomenon, although with different characteristics, was already documented in a TDH-39 loudspeaker,[8] and was attributed to a change in the mechanical properties of some vibrating membranes exposed to lower surrounding ambient pressure levels. This is not a general rule, since Rasmussen analyzed the behavior of different condenser microphones under hypobarism, such as the Bruel & Kjaer 4190 used in this study as reference microphone, without detecting relevant changes in its performance within a wide range of pressure variations.[13] However, the possibility of a different performance of HAs at high altitudes must be taken into account and in our study this was particularly emphasized by the analysis conducted at 15,000 ft.

The receiver's performance deserves particular attention, since it cannot be compensated by following the amplification process used by the HA amplifier, as in the case of the microphone. This aspect, along with the mild effects that we observed on the input transducer, indicate that the changes in its outgoing electric signal during hypobarism can be considered negligible for the global performance of the HA.

Conversely, the receiver's output reduction, caused by air rarefaction, was more evident, although in our study, variations up to 9 dB could be observed only when 15,000 ft (4572 m) was reached (Fig. 3). At high altitudes, the irregular

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decrease of the acoustic output across frequencies (Fig. 3) was also related to a mild shift of the receiver's I/O curve in the frequency domain, which induced more evident intensity changes at the level of the acoustic resonance peaks, similarly to what was documented in a previous report on loudspeakers.[8] As a matter of fact, the test at 9000 ft (2743 m) evidenced only minor changes in the receiver's performance, so that a safe utilization of such device within the physiological threshold of 10,000 ft (3048 m) can be argued. On the contrary, at higher altitudes, some correction parameters should be considered to preserve optimal performance of an HA, although this should be adapted to the different transducer models and to their performance under hypobaric conditions. Such a finding might be of particular interest when the use of HAs is required by professional regulations, as in the case of flight certification, which may imply their use at altitudes much higher than 10,000 ft. In recent years, the European Aviation Safety Agency has introduced the possibility of an in-flight use of HAs for aircrew members within the medical certification assessment.[6] More specifically, the "Hearing Aid Limitation (HAL)" can be issued only when such devices provide an "optimal hearing function, are well tolerated and suitable for aviation purposes." Therefore, a recalibration of their I/O function at altitudes higher than 10,000 ft might be needed.

In conclusion, our findings showed that HAs can tolerate very rapid pressure changes and the exposure to high altitude environments, at least as far as the two models of transducers that were tested in this study showed. HAs can also be considered as a valuable and safe method to improve in-flight communication of aircrew members affected with hearing loss without significant derangements when the cabin altitude is kept below 10,000 ft (i.e., in agreement with the current standards). When higher ambient altitudes are reached, recalibration of the HA acoustic output should be considered to preserve adequate hearing levels. This goal might be reached with dedicated amplification setups, to be selected according to the specific HA characteristics as well as to the patient's needs.

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