The evaluation of in-chamber sound levels during hyperbaric oxygen applications: Results of 41 centres

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Key words
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Abstract
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Introduction: Noise has physical and psychological effects on humans. Recommended exposure limits are exceeded in many hospital settings; however, information about sound levels in hyperbaric oxygen treatment chambers is lacking. This study measured in-chamber sound levels during treatments in Turkish hyperbaric centres.
Methods: Sound levels were measured using a sound level meter (decibel meter). All chambers were multiplace with similar dimensions and shapes. Eight measurements were performed in each of 41 chambers; three during compression, three during decompression, and two at treatment pressure, one during chamber ventilation (flushing) and one without ventilation. At each measurement a sound sample was collected for 25 seconds and A-weighted equivalent (LA_{eq}) and C-weighted peak (LC_{peak}) levels were obtained. Recorded values were evaluated in relation to sound level limits in regulations.
Results: The highest sound level measured in the study was 100.4 dB(A) at treatment pressure while ventilation was underway and the lowest was 40.5 dB(A) at treatment pressure without ventilation. Most centres had sound levels between 70 dB and 85 dB throughout the treatment. Ventilation caused significant augmentation of noise.
Conclusions: The chambers were generally safe in terms of noise exposure. Nevertheless, hyperbaric chambers can be very noisy environments so could pose a risk for noise-related health problems. Therefore, they should be equipped with appropriate noise control systems. Silencers are effective in reducing noise in chambers. Thus far, hyperbaric noise research has focused on chambers used for commercial diving. To our knowledge, this is the first study to investigate noise in hospital-based chambers during medical treatments.

Introduction

There are miscellaneous definitions for noise in acoustics or phonology, but it can simply be defined as unwanted sound. Basically, there is no difference between sound and noise. Sound waves can be perceived as speech, music or noise depending on the individual.[1] Noise in health sciences is accepted as a source of stress and has long been known to have physical and psychological effects on humans.[2] Hearing impairment known as noise-induced hearing loss (NIHL) is the most apparent impact, however, many other influences on body functions have been observed. It has been associated with high blood pressure and increased coronary heart disease risk as well as hormonal and psychosocial disturbances.[3–5] In addition, there is growing evidence that noise contributes to burnout and error risk related to impaired concentration and miscommunication.[6,7]

NIHL may develop after exposure to impulsive (instant high level) sounds. The human ear senses sounds between 0–140 dB. Whereas a noise of 120 dB causes discomfort in the ear, sounds between 125–135 dB cause pronounced pain. At 140 dB, tympanic membrane rupture may be seen and permanent damage might occur.[8,9] Prolonged and repeated exposure to lower sound levels can also deteriorate hearing and cause gradual impairment. To avoid damage, noise standards that set out exposure limits and measures to be taken for hearing protection have been determined.[2]

There are various sources of noise in daily life. Humans are exposed to noise from industry, transportation, recreation and work. According to the World Health Organization (WHO), the maximum level of noise exposure should not exceed 85 dB in daily life. Work is one of the places that humans spend most of their time and are exposed to noise. Therefore, regulations for worksites have also been developed and maximum sound levels at which an employee can work with respect to time are well defined. These regulations also mandate actions such as hearing protections or reducing sound at source when limits are exceeded. Noise standards

Table 1
Maximum daily exposure times with respect to sound levels according to Turkish regulations

Sound level (dB)	Exposure time (hours)
85	8
87	6
90	4
92	3
95	2
97	1.5
100	1
105	0.5
110	0.25

vary among countries, but generally, in developed countries the acceptable maximum noise level is 85–90 dB(A), for five days a week and eight hours per day. A'3dB doubling factor' which implies that an increase of three dB in sound level requires a reduction of exposure time by two, is applied to these limits.[10] Occupational noise standards in Turkey are defined in the legislation *Regulation on the Protection of Employees from Noise-related Risk*s and these are similar to other global standards.[11] The maximum allowed sound levels with respect to exposure times in Turkish regulations are given in Table 1.

Hospitals are worksites where occupational noise can be encountered. Medical equipment, alarms, portable vehicles, personnel activities, communication systems, and air conditioning and ventilation systems are some sources of noise.[12] Although not mandatory, there are recommendations for hospital noise. Sound levels should not exceed 30 dB and peaks should not be over 40 dB in hospitals according to the WHO. Similarly, the Environmental Protection Agency (EPA) recommends a maximum sound level of 45 dB(A).[1,13] It has been shown in many studies that these limits are exceeded, especially in intensive care units.[14,15]

Hyperbaric oxygen treatment centres can also be noisy environments. According to the European regulation for pressure vessels for human occupancy (EN 14931), the average sound level should not exceed 70 dB(A) at treatment pressure with (maximum) ventilation on, and 90 dB(A) during compression and decompression.[16] Studies have been performed in chambers used in diving operations but few studies have focused on sound levels in hospital-based chambers. The aim of this study was to measure in-chamber sound levels in different hyperbaric oxygen treatment (HBOT) centres in Turkey and to evaluate the possible effects on patients and health care providers by comparing the measured sound levels with international standards.

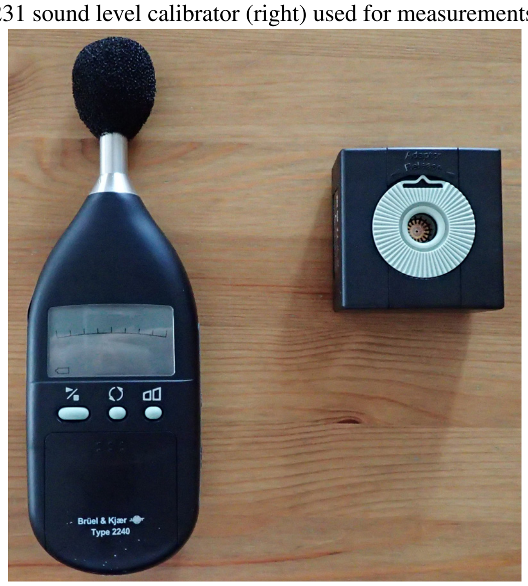
Methods

The study was approved by our Institutional Review Board. It was supported by Istanbul University Scientific Research Fund (Project No.: 20326).

All HBOT centres in Turkey were contacted either by phone or e-mail and the study was explained in detail. Sound level measurements were planned with centers that agreed to participate. Measurement days were randomly selected but were always weekdays on which treatments were conducted. All participating centres had cylindrical, steel multiplace chambers with similar dimensions. All chambers were equipped with similar furnishings, piping systems and internal instruments. Compression and decompression rates were similar for all chambers and ranged between 10−12 kPa·min^{-1} (equivalent to 1−1.2 metres' seawater [msw] per minute). Sound levels were measured in the chamber; three times during compression, three times during decompression and two times at treatment pressure (243 kPa, [2.4 atmospheres absolute [atm abs] pressure]), one with ventilation and one without. In this context 'ventilation' refers to a process where gas is flushed into and vented from the chamber at equivalent rates such that the pressure within remains constant. In many jurisdictions this is referred to as 'flushing'. Measurements during compression were performed between 15−30 kPa, 60−75 kPa and 120−134 kPa pressures (1.5−3 msw, 6−7.5 msw and 12−13.5 msw depth equivalents). Measurements during decompression were performed in reverse order.

Sound level measurements were performed using a Bruel & Kjaer Type 2240 sound level meter (SLM) (Bruel & Kjaer, Naerum, Denmark) and Bruel & Kjaer type 4231 sound level calibrator which is compatible with the SLM (Figure 1). This device is an integrated – average field

Figure 1
Bruel & Kjaer Type 2240 SLM (left) and Bruel & Kjaer type 4231 sound level calibrator (right) used for measurements



Type 1 sound meter and complies with International Electrotechnical Commission (IEC) 61672-1 standards. It can measure sound pressure levels between 30 to 140 dB(A) and frequencies between 20 Hz to 16 kHz. The device can operate between -10°C and 50°C and for 16 hours on two 1.5 Volt LR6/AA alkaline batteries. It weighs 245 g and is portable so can be carried easily to measurement spots. Information about the compatibility of device in hyperbaric conditions was provided by the manufacturer prior to performing the study.

All measurements were performed during routine HBOT sessions. The SLM was placed at least one metre away from the sides of the chamber and 130 cm above the floor, which would be the ear level of a sitting patient. At each measurement interval, a sound sample was collected for 25 seconds and A-weighted equivalent continuous sound levels (LA_{eq}) and C-weighted peak sound levels (LC_{peak}) were obtained. LA_{eq} defines the equivalent of total sound energy measured over a period of time and is basically the average sound level. LC_{peak} shows the instantaneous highest sound level. Before each measurement during compression and decompression the SLM was calibrated because the pressure in the chamber changes continuously. The calibration level was 94 dB.

Measured LA_{eq} and LC_{peak} values in dB(A) and dB(C), respectively, were recorded in Microsoft Excel® 2016. Recorded values are presented descriptively and evaluated in means of sound level limits in regulations. Statistical analysis was performed using the Med-Calc® for Windows (version 11.2.1.0). Data distribution was evaluated using the Kolmogorov-Smirnov test and Student's *t*-test was used to compare paired samples. Significance was accepted at $P < 0.05$.

Results

Forty-one HBOT centres from eight different cities participated in the study. The highest LA_{eq} (equivalent continuous sound level) measured in the study was 100.4 dB(A) at the treatment pressure during ventilation and the lowest was 40.5 dB(A) at treatment pressure without ventilation. The highest and lowest sound levels recorded at compression, treatment depth and decompression throughout the study are given in Table 2. The distribution of centres with respect to sound levels at each sample collection interval is given in Table 3.

Most of the centres had sound levels between 70 dB(A) and 85 dB(A) throughout the treatment, whereas only four were lower than 70 dB(A). These four were those with sound levels lower than 70 dB(A) at treatment depth both with ventilation on and off. Thirteen centres exceeded the 85 dB(A) limit at treatment depth with the ventilation on but all were below this limit when the ventilation was off. The sound levels were found to be significantly higher when the ventilation was on in all centres. ($P < 0.001$)

Other than the four centres that were below 70 dB(A) throughout treatment, another three and four centres were below 70 dB(A) all through compression and decompression, respectively. Three exceeded the 85 dB(A) in all three measurements of compression. Only one centre was over 85

Table 2

Highest and lowest L_{eq} and L_{peak} values during compression, treatment depth and decompression in the study; Vent. = ventilation

Parameter		Compression	At treatment pressure		Decompression
			Vent. on	Vent. off	
L_{eq} dB(A)	Highest	95.6	100.4	79.0	94.0
	Lowest	58.6	63.9	40.5	47.7
L_{peak} dB(C)	Highest	109.3	113.6	99.1	106.7
	Lowest	76.0	85.7	74.5	77.5

Table 3

Number of centres with respect to measured sound level in each sample collection interval. C1, C2 and C3 – measurement intervals at the beginning, midway through and towards the end of compression; D1, D2 and D3 – measurement intervals at the beginning, midway through and towards the end of decompression; Vent. = ventilation

Sound level dB(A)	Compression (*n*)			Treatment depth (*n*)		Decompression (*n*)		
	C1	C2	C3	Vent. on	Vent. off	D1	D2	D3
≤ 70	15	11	8	4	19	10	13	16
70.1–85	23	25	27	24	22	29	26	22
> 85	3	5	6	13	–	2	2	3
> 90	2	3	3	5	–	2	1	2

dB(A) all through decompression. Few exceeded 85 dB(A) in one or two measurement points during compression or decompression.

When the '3 dB doubling factor' was taken into account, a sound level of 95 dB(A) at treatment pressure and 105 dB(A) during compression and decompression could be permissible. In this case, only three centres exceeded the limit at treatment pressure with ventilation working. None remained over the limits all through treatment. Also, none exceeded the allowed LC_{peak} levels in any sample collection interval.

Discussion

Sound is a pressure wave that is formed by a vibrating object and travels through a medium by transferring energy from one particle to another. Sound pressure, which is the deviation in atmospheric pressure by a sound wave, is the most important parameter to understand its effects. The human ear can sense sound pressure between 20 µPa to 100 Pa. These two values are separated by a factor of more than a million, thus it is not practical to obtain sound pressure measurements in a linear scale of Pa since the range would be too wide. Accordingly, sound pressure level (SPL), which is the logarithmic ratio of a measured value to a reference value, namely 20 µPa is used for acoustic parameters. SPL is measured using a SLM and expressed in decibels (dB).[1]

Another parameter important in sound measurements is frequency weighting. Frequency is the number of sound waves passing a fixed point per second and measured in Hertz (Hz). The human ear can hear between 20 Hz to 20 kHz but is more sensitive to frequencies between 500 Hz to 8 kHz and less sensitive to very high and low pitches. A measurement device, on the other hand, does not have this selectivity. To ensure that a SLM measures what a human ear perceives, frequency weighting that filters the relative strength of various frequencies is used. The most common one is A-weighting, as it is accepted to be the most approximate frequency response to human hearing.[8] It cuts off the very low and very high frequencies that an average human cannot hear. C-weighting, on the other hand, also takes extreme high and low frequencies into account and is more commonly used for measuring peak sound levels. Measured sound levels are expressed as dB(A) or dB(C).

Hearing under pressure may differ from hearing at atmospheric pressure due to changes in acoustic parameters of the media through which a sound wave travels.[17] It has been shown that the hearing threshold increases underwater because bone conduction, which has less contribution to hearing compared with air conduction, becomes the major way sound is transmitted when the tympanic membrane is in contact with water (known as wet ear).[18] In other words, humans are less sensitive to sound underwater and higher sound levels would have less impact.[19] Despite this, studies have revealed divers may face noise-induced hearing impairment.[20,21] In dry hyperbaric environments, on the other hand, threshold shift has not been detected either with air or other gases, so susceptibility to noise is not thought to be different from normal air.[18] In addition, chambers are confined environments and can be noisy due to the turbulence generated from high pressure gas merging into still gas and passing through pipes during compression and ventilation. Also, cylindrical chambers are highly reflective for sound waves.[18,22] In fact, a study that questioned patient experience of hyperbaric treatment in Australia showed that noisiness in the chamber was one of the primary reasons for discomfort.[23] Yet, there are only a few studies discussing sound levels in chambers even though noise can reach sufficiently high intensities as to cause health hazards during hyperbaric interventions.

In a 1970 report, sound levels were measured in a US Navy chamber during compression and decompression with average rates of 210 $kPa \cdot min^{-1}$ (21 $msw \cdot min^{-1}$) and 180 $kPa \cdot min^{-1}$ (18 $msw \cdot min^{-1}$), respectively. The sound levels were over 100 dB(A) in both.[24] Later, sound levels were measured in a US Navy chamber during compression and decompression, both at 180 $kPa \cdot min^{-1}$ (18 $msw \cdot min^{-1}$) and chamber ventilation at different depths. Almost all measurements read over 110 dB(A) and the highest sound level was 121 dB(A) at a pressure of 150 kPa (15 msw).[25] A series of measurements performed in British Royal Navy chambers revealed similarly high sound levels.[18] In recent decades, hospital-based chambers, which are generally operated at much lower compression and decompression rates than those used in the above studies and which are fitted with newer systems and equipment have prevailed. Until this study, there has been a lack of information regarding noise in these chambers, although they are mostly reserved for patients who are likely less used to and are expected to be more sensitive to noisy environments compared with industrial and navy divers.

In this study, sound levels in 41 different hyperbaric chambers were measured during compression, decompression and at treatment pressure. It was found that most of the chambers were under occupational noise level limits during treatment, although most exceeded the European pressure vessel standard at treatment pressure. Also, it was seen that ventilation increased the noise in the chamber significantly. Yet, chambers in this study can generally be considered safe in terms of noise for usual two-hour treatments. However, if longer treatment tables, such as the US Navy Table 6, are needed, some chambers may entail a risk. Noise has been shown to have adverse effects on patient outcomes, besides well-known noise-related health problems.[26] Studies investigating effects on patients suggest that prolonged noise exposure is related to slower healing, longer hospitalisation and increased pain medication.[27] In this regard, use of hearing protection may be considered for longer treatments or during ventilation in chambers in which higher sound levels are encountered.

The measured sound levels reported in this study are lower than in previous reports; however, the intended purpose of navy diving chambers, much higher compression rates and variability of measurement techniques are notable in terms of this comparison. A major difference that should not be ignored is the presence of advanced silencers in the chambers in which we performed measurements. Silencers and mufflers are effective ways of controlling noise in hyperbaric chambers. They are usually installed at inlets of air pipes or exhausts and reduce the sound transmission while allowing the free flow of air. Attenuation in the range of 20 to 40 dB was shown in a study performed in chambers and diving bells equipped with different designs of silencers.[22] Tests were conducted at pressures between 101.3 kPa (1 atm abs) in air to 608 kPa (6 atm abs) and heliox. In another study where four different silencers were compared during decompression from 506 kPa (5 atm abs), it was seen that the measured sound levels varied greatly.[17] Thus, the presence of a silencer and its design and attenuation capacity are all important for effective noise control. This may explain the variability of sound levels in our study since all chambers were equipped with silencers. Cladding chambers with sound absorbent materials might be another option for noise control; however, it should not represent a fire risk or cause hygiene problems.

Staff working around the chamber, especially chamber operators, may be exposed to noise, probably for long hours. The present study focuses on the noise in the chamber and does not reflect the exposure in the vicinity but such measurements may provide an insight. Sound levels around chambers should also be determined for the prevention of possible long-term health hazards for staff working in hyperbaric units.

LIMITATIONS

It is known that even small changes of conditions within a space may cause alterations in the sound field. Despite the similar structure of the chambers, the number of occupants during measurements was not the same. Also, the interior designs differed slightly. Therefore, a direct comparison of the chambers in terms of noisiness is not possible and was not the aim of the study. In addition, for a given chamber the measured sound level could have been different with a different number of occupants or a change in interior configuration, but the size of this effect is not predictable. The effects of chamber occupants and interior design on sound levels may be investigated in further studies.

Another important point in noise measurement is its effect on people. Even if the measured sound levels are within permitted limits, it is possible that patients and staff perceive it as disturbing due to hearing differences or confined space anxiety. Therefore, the impact of measured sound levels on comfort and health also needs to be evaluated. Further studies focusing on the perception of occupants should be conducted to claim that hyperbaric chambers are truly safe in terms of noise.

Conclusion

This study revealed that hyperbaric chambers can be noisy during ventilation and sound levels in the chamber may exceed safe limits when longer treatments are administered. In this regard, an assessment for compliance with noise regulations can be recommended for all hyperbaric chambers. Measures to minimize the impacts can be considered for chambers or operations that would pose a risk. Also, national legislations on hyperbaric chambers should be regulated for noise standards and chamber manufacturers should be obliged to comply with requirements. To our knowledge, this is the first study to focus on noise during treatments in hospital-based hyperbaric chambers and may serve as a pilot study for further research.

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