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Aerodynamic Noise in Hyperbaric Chambers: Assessment and Possible Mitigation

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Summary
The use of hyperbaric chambers prevailed in medical therapy for vascular diseases and for outbreaks of embolism in emergency situations. This implies the achievement of environmental pressure conditions from two to three times higher than the atmospheric one, in such a short time to require delivery of the air flow that leads to very high intensity noise. The attenuation of this noise is usually performed through the installation of silencers at the air outlets. In this work a series of noise measurements is presented, carried out inside the chamber, limited to the periods it is available to maintenance activities, in various conditions of the opening of the air inlet valve, with and without silencers mounted on the air outlet nozzles and with or without different layers of floor covering. In order to characterize the attenuation capacity of the silencers and to verify that the air flow is the most significant source of noise, a series of noise measurements is also presented, carried out in the open field while emptying a pressurized tank, in various conditions of opening of the exhaust valve, for different types of silencers placed at the outlet. The analysis of the frequency spectra allows to evaluate the behaviour of these devices, at the light of theoretical predictions concerning the aerodynamic noise. The results suggest that the optimization of some of the flow parameters and the operating conditions of the chamber can contribute significantly to the reduction of noise, with a consequent net improvement of such device, in particular under operating conditions of emergency.

PACS no. 43.50.Cb, 43.50.Gf, 43.50.Nm

1. Introduction

Hyperbaric chambers are hospital treatment facilities, able to withstand high pressures and to accommodate people who need hyperbaric decompression treatments or therapy for vascular diseases, or in more serious conditions, for outbreaks of embolism [1, 2, 3, 4, 5, 6, 7, 8]. The air for filling the chamber is generally taken from the external environment, purified and pressurized by a compressor. It can be introduced directly into the chamber, or stored in cylinders or pressure vessels exceeding the maximum load of the chamber so as not to need a continuous use of the compressor, which is therefore put into use only during the charging of the cylinders. Especially in emergency conditions, the pressure inside the chamber (two to three times higher than the atmospheric one) has to be reached quickly. This involves the use of large flows of incoming air, that may generate high-intensity noise, which is an element of discomfort to patients and caregivers within the chamber and possibly to those involved in the control panel [9, 10, 11].

In this paper we report the results of a series of measurements made in a chamber in the Hyperbaric Therapy Center of the Policlinico Umberto I in Rome, performed in order to provide guidance on possible interventions for the attenuation of noise levels. The aim of the work is to analyse the present operating conditions of a hyperbaric chamber, relative to noise reduction solutions usually performed. Due to the presence of other sources of risk represented by oxygen fire and toxic effects, noise disturbances are usually left behind, though in standard therapeutic conditions, they represent a highly disturbing source for the suffering patients. In this paper, then, interest has been focused on the identification of the main noise sources, in order to evaluate the effectiveness of possible interventions on the very same or future chambers to be used. The sound pressure level at different points in the chamber has been detected to verify the presence of stationary conditions of the acoustic field, under different layers of floor covering, to assess the effect of absorption, and in the presence or absence of silencers at the output ports of entry, to characterize the attenuation properties. The behaviour of a few sample silencers have then been evaluated in an open air surrounding in order to eliminate at the most any influence due to enclosure resonances and disturbing bodies.

2. Measurements in hyperbaric chamber

The hyperbaric chamber of the Policlinico Umberto I is shown in Figure 1 left. It consists of a central secondary

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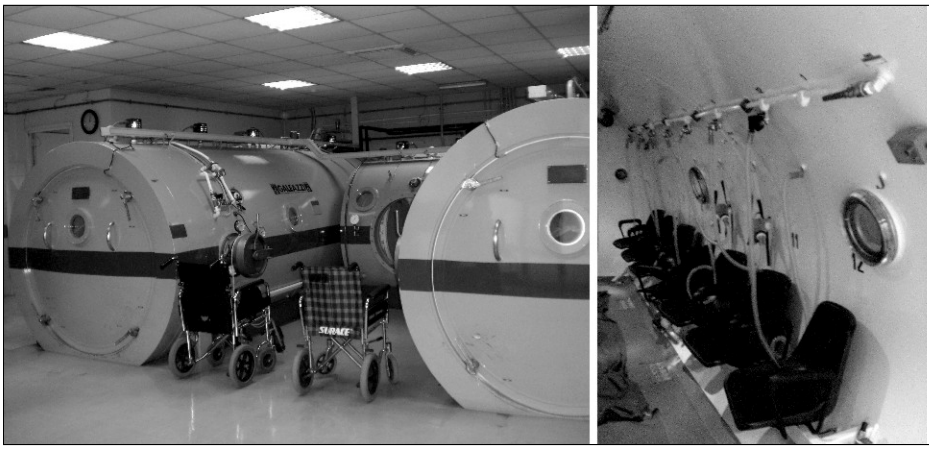

Figure 1. Hyperbaric Therapy Center at Policlinico Umberto I; left: the chamber seen from outside; right: the chamber inside.

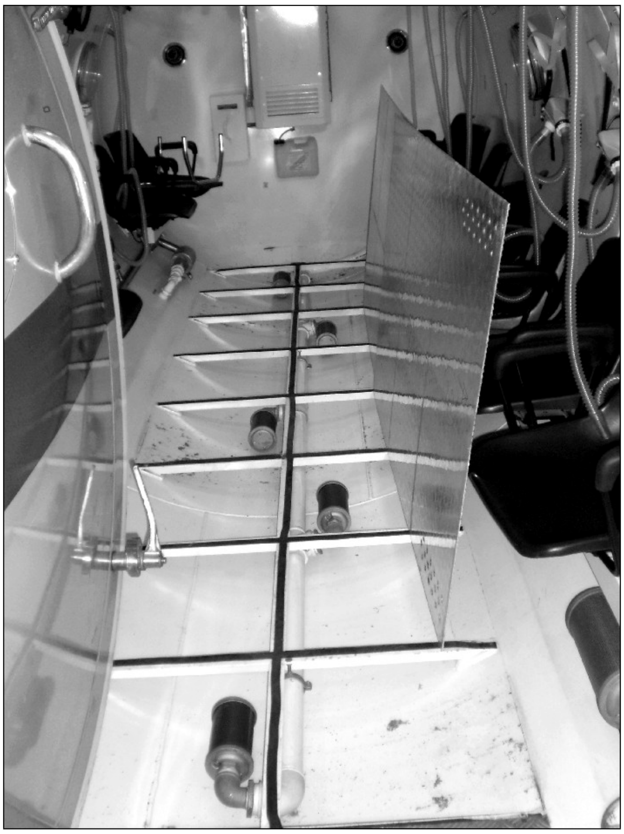

Figure 2. Hyperbaric Therapy Center at Policlinico Umberto I in Rome: inside of the Beta chamber with the floor removed.

chamber, communicating with two main rooms on each side. The main chamber on the right side in the same picture, called “Camera Beta” is a cylindrical chamber multiplace, represented in Figure 1 right, of diameter $D \sim 2\,\mathrm{m}$ and length $L \sim 5.0\,\mathrm{m}$. The chamber is equipped with twelve seats, each numbered and accompanied by a mask for oxygen supply. The floor covering the bottom of the chamber is a metal plate on which there rests a cover of linoleum; the complementary boundary surface of the chamber is a rigid steel wall, that makes it resemble to an echoic chamber with resonance modes along its axis, that will be referred to later. After removing the floor, the bottom of the chamber appears as shown in Figure 2.

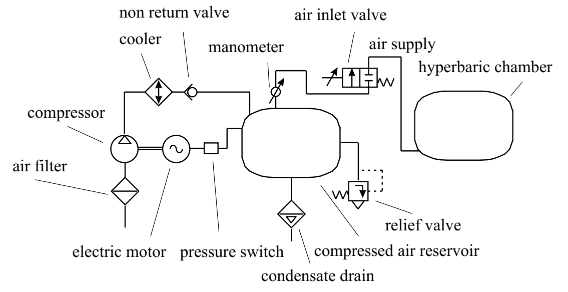

Figure 3. Scheme of the air supply system; typical pressure values in the reservoir are 8–10 atm.

As it can be seen, the air manifold, whose diameter is 2 inches (5.08 cm), runs lengthwise beneath the floor of the chamber, at the centerline. Five air vents depart from it, each equipped with a absorptive/reactive silencer of the type Atomuffler by Allied Witan Company. A simple scheme of the air supply system to the chamber is shown in Figure 3. In therapeutic conditions, the air inflow speed can be of the order of 120 m/s through the air inlet valve, as it can be deduced from the time necessary for getting the correct chamber pressurization, since direct measurements are not directly available, nor with regard to the valve nor with regard to the input velocity; in emergency conditions, the flow through the air inlet valve can be supersonic flow.

In order to check the modal distribution along the axis, we preliminarily performed measurements with the microphone set at three different positions on the very axis of the chamber, that correspond to $x = 0$, 1.25, 2.5 m from the entrance end wall, to sample the very first modes for indexing purpose. Figure 4 schematically represents the positions of the sound level meter along the x axis and the theoretical pressure field of the first three resonant longitudinal modes. In Figure 5 the sound level spectra are shown at each position, where the values of Leq result equal to 88.1 dB, 84.5 dB and 83.7 dB respectively. This figure shows that the measurements performed inside the chamber are reproducible. With regard to the central position spectrum ($x = 2.5\,\mathrm{m}$), the maximum level occur-

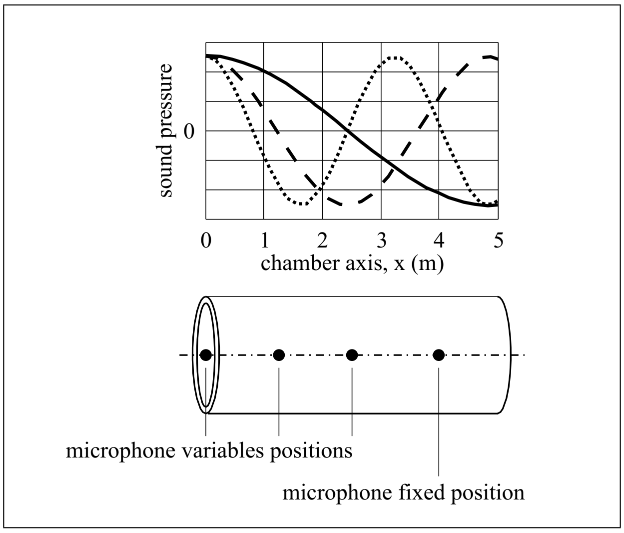

Figure 4. Positions of the sound level meter along the chamber axis and pressure field of the first three resonant longitudinal mode.

ring at 40 Hz, corresponding to the first resonance mode, is lower with respect to the other positions ($x = 02$ m and $x = 1.25$ m), coherently with the expected presence of a node at that position. With regard to the intermediate position spectrum ($x = 1.25$ m), the maximum level occurring at 63 Hz, corresponding to the second resonance mode, is lower with respect to the other positions ($x = 0$ m and $x = 2.5$ m), once again coherently with the expected presence of a node at that position. With regard to the third harmonic mode, the same consideration can be drawn for the central position that was given for the first mode; however, difference between curves is slightly reduced probably due to presence of additional radial modes, with respect to the longitudinal pure ones, more evident at higher frequencies.

To evaluate the aerodynamic noise, measurements were made of sound pressure in different flow conditions and for different configurations, using a sound level meter class 1 (the SOLO model of 01dB). All measurements were performed with the entrance door open, so as to allow inside pressure not to change and flow noise to be steady at its maximum value on time; each measurement overall duration was 16 s. A summary of some of the tests, made with the sound level meter placed on the axis of the chamber at a distance of about 1 m from the back wall, is shown in Table 1, where the sound level values for three different degrees of opening of air inlet valve (12%, 24%, 48%) are reported in dBA. The data in the columns refer to different configurations, identified with the yes / no depending on the presence or absence of silencers at the entry sections, the aluminum floor and the linoleum cover.

For a first assessment of the effects due to individual elements, the spectra of sound level were analyzed at thirds of octave, for each of the five conditions listed in the table, grouped in each plot for the very same values of the valve opening. In Figures 6, 7 and 8 the results of the measurements reported in Table I are shown that permit to assess the effect of each single item in the chamber set-up for the different opening degrees.

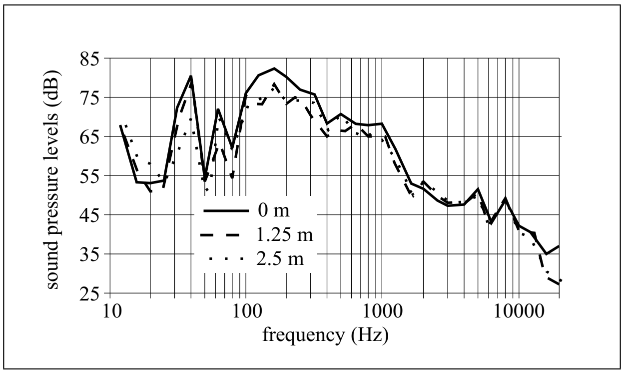

Figure 5. Sound pressure level at three positions along the chamber axis.

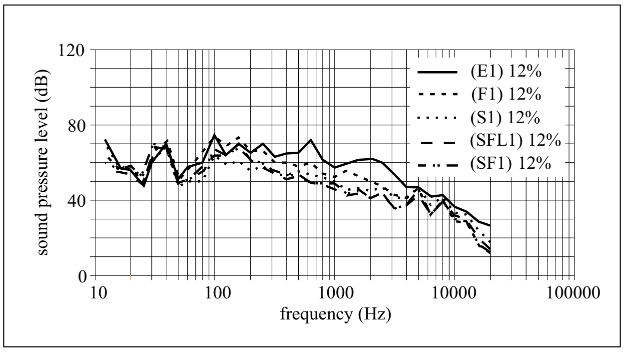

Figure 6. Frequency spectra of sound pressure level for the five configurations of Table I in case of opening degree equal to 12% (numbers in the legend refer to measurements labeling in Table I).

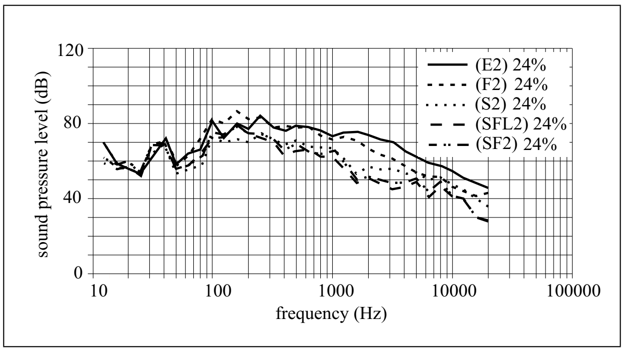

Figure 7. Frequency spectra of sound pressure level for the five configurations of Table I in case of opening degree equal to 24% (acronyms in the legend refer to measurements labeling in Table I).

It is a general feature of all the measurements performed that the levels increase with the opening degree of the valve for the supply of the air in the chamber, due to the increase of the flow speed of the incoming fresh air. It is also common to all plots the presence of relative minima around a central frequency of 50 Hz and of two relative maxima, around a central frequency of 40 Hz and around a central frequency of 100 Hz The corresponding wavelength for the minimum values is the central value $\lambda =$

Table I. Summary of some measurements made in the chamber: E empty, S silencers, F floor, L linoleum. Sound level meter on the longitudinal axis, at 75 cm from the ceiling and about 1 m from the back wall.

test	E1, E2, E3	S1, S2, S3	F1, F2, F3	SF1, SF2, SF3	SFL1, SFL2, SFL3
Silencers	no	yes	no	yes	yes
Floor	no	no	yes	yes	yes
Linoleum	no	no	no	no	yes
Leq (dBA) at 12%	73,8	60	67,4	61,2	61,3
Leq (dBA) at 24%	85,9	75,5	84,6	75	73,6
Leq (dBA) at 48%	115,6	98,3	112,8	97,7	95

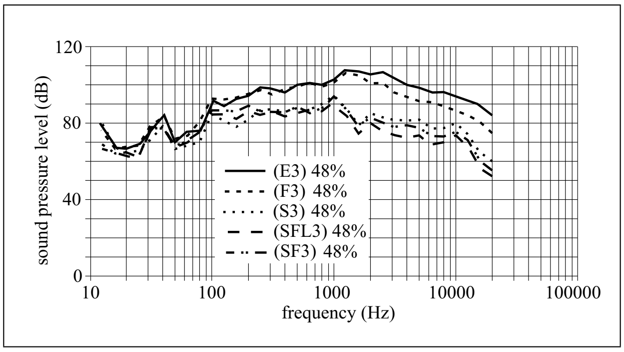

Figure 8. Frequency spectra of sound pressure level for the five configurations of Table I in case of opening degree equal to 48% (acronyms in the legend refer to measurements labeling in Table I).

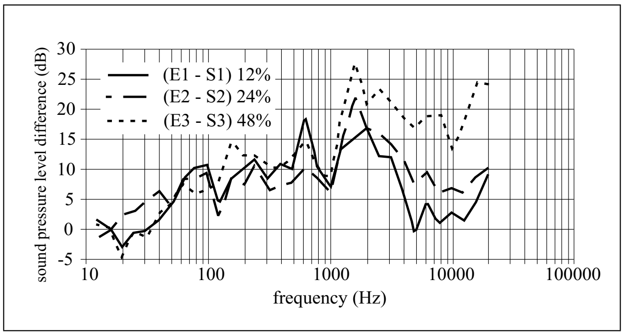

Figure 9. Effect of the silencer: differences in frequency spectra of sound pressure level in the presence and absence of silencers (acronyms in the legend refer to measurements labeling in Table I).

6.8 m; for the first maximum values, it is the central value $\lambda = 8.5$ m; for the second maximum values, it is the central value λ 3.4 m. This values correspond to first antiresonance and first and third harmonic resonances modes, respectively, along the longitudinal size of the chamber, as represented in Figure 4. A peak belonging to the second harmonic could not be measured, which is most likely caused by the chosen position of the sound level meter along the axis of the chamber (at $d = 4$ m from the entrance end wall of the chamber).

To assess the effects on the noise due to silencers, floor and linoleum, we analyzed the trend of the difference between the values of the spectral level in the absence of all the three elements and those in case there is at least one element.

Figure 9 shows the trend of this difference due to the presence of silencers only (measurements S1, S2, S3): the values of this differences in terms of Leq result 13.8, 10.4 and 17.3 for the three different valve openings, as expressed in dBA (as directly deduced from Table I) and 6.3, 8.5 and 15.7, as expresses in linear dB. It is noted that at low frequencies the values fluctuate slightly above zero, and show a steady growth of about 3 dB per octave in the range between 12.5 and 1000 Hz, which means that in this frequency range silencers do reduce the noise quite effectively, while their efficiency decreases at frequencies above 1600 Hz. This latter effect is more evident in the case of lower flow speeds (i.e. for small opening of the valve); for higher flow speeds, higher frequencies are generated so that the resistive contribution to the noise reduction is more evident [12, 13]. However, also for higher flow speeds the decrease occurs. This is probably due to additional contribution at higher frequency of noise produced by sources, as the air supply valve, that cannot be directly reduced by the silencers. The evident dip of the attenuation level around 1000 Hz in all three series of measurements could be reasonably attributed to a resonance in the structure of the silencers at that frequency, since in air, the half-wavelength at 1000 Hz is approximately 15 cm, corresponding to the length of the internal volume of the silencers used. A mitigating effect of the floor on the noise (test F1, F2, F3) results from Figure 10; the oscillations around zero at lower frequencies, which are present in all three sets of measurements, show the ineffectiveness of the floor on the noise reduction up to about 1000 Hz, while the similarity of the oscillations suggests that the peaks are due to resonances of the structure of the floor. The corresponding frequency are consistent with the normal frequencies of a rectangular aluminum plate supported at the four edges, to which, at first approximation, the panels of the floor can be equated [14]. However, the effect cannot really be assimilated to transmission loss of the plate - which would be much more effective - since the different elements disposition is well off the protocol conditions and sound may cross over the floor plate through alternative paths; experimental data are, then, simply indicative of the noise reduction obtained with the actual chamber structure. Namely, attenuation is confined to values below 10 dB, much below the theoretical prediction in terms of Transmission Loss for an aluminum plate with

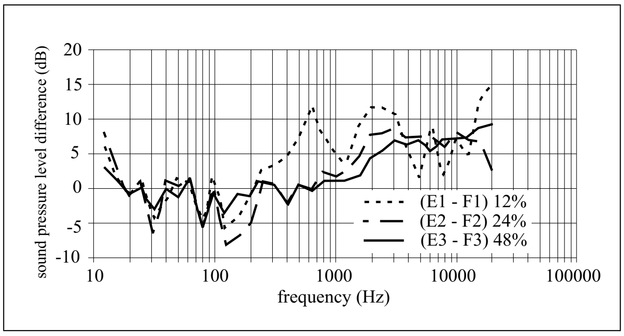

Figure 10. Effect of the floor: differences in frequency spectra of sound pressure level in the presence and absence of the floor (acronyms in the legend refer to measurements labeling in Table I).

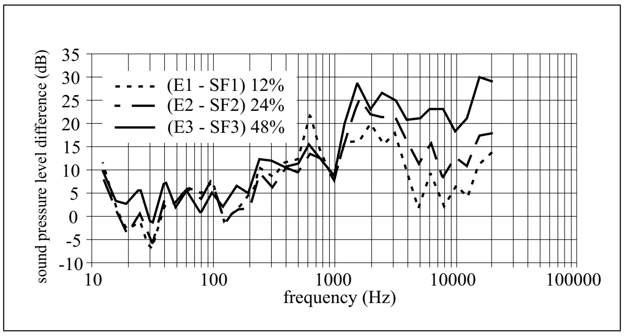

Figure 11. Combined effect of silencers and floor: differences in frequency spectra of sound pressure level in the presence and absence of silencers and floor (acronyms in the legend refer to measurements labeling in Table I).

thickness of the order of 1 cm, similar to the experimented one, inserted between two isolated infinite volumes [15]. Although the coupled separated volumes might be assimilated to reverberating ones, data do ascertain an insufficient isolation closing between the adjacent volumes.

The combined effect of silencers and floor is represented in Figure 11, where the difference is reported between spectral levels obtained with the two items included and those with no items at all. The spectra do match quite closely with those that one would derive by simply summing up the single attenuation spectra of the floor and the silencers, separately.

3. Measurements in open field

The silencing properties of a few sample silencers have then been evaluated in an open surrounding in order to eliminate at the most any influence due to enclosure resonances and disturbing bodies. Previous to further considerations on the attenuation efficiency of the tested silencers, attention should be focused on the way the insertion of silencers acts on noise production and reduction in the chamber. Noise sources, indeed, are the aerodynamic noise directly produced at the outlet by the incoming air flow and the vibrations produced on different structures anyhow involved by the air flow. Silencers act on the former source in a way that cannot be just considered as the one performed by a filter on a pre-existing noise: their insertion, indeed, consistently perturbs the outgoing flow, then the noise therein produced, and their overall effect cannot be a priori resumed by a transfer function, without knowing the speeds and the flow regimes of mass that develop with no silencer and once the silencer has been fitted respectively [16]. Their efficiency has to be experimentally tested in the different conditions, or pressure gradients, that cause the air flow.

The measurements have then been performed during the very first phase of the evacuation process of a pressurized tank, 2000 liters by volume from the initial pressure of 8 atm; pressure does substantially remain unchanged during the duration of the measurements. The silencers were positioned at the exit discharge valve, whose opening degree could be properly varied. In this way the tank was used as a source of pressurized air for the measurements and the silencers were mounted in a position similar to that in use inside of the chamber, where they are set at the air flow outlet. A SOLO model class 1 sound level meter of 0.1 dB S.r.l. was positioned at $L = 4\,\mathrm{m}$ distance from the tank valve along the axis of the air jet, $h = 1.5\,\mathrm{m}$ above ground level. Each measurement overall duration was 16 s.

In order to evaluate the efficiency of the silencers at different flow configurations, measurements have been preliminarily performed of the noise produced by the free air-jet with no silencers mounted, for different values of the opening degree of the valve. In order to make a correct comparison of measurements for the efficiency determination of the silencers, and avoid the direct action of the air jet perturbing the sound level meter, with local production of turbulent air vortices data have been used of free jet noise levels at slightly larger angles with respect to the axial positioning [14]. Measurements have been successively performed on three different silencers; one of these is the Atomuffler employed in the hyperbaric chamber of the Policlinico Umberto I, 154 mm length, 90 mm diameter, already experimented on and shown in Figure 12 (left); the others are two absorptive/reactive models of SMC Corporation (ANA1 series), shown in Figure 12 (right), of 1" (132 mm length, 50 mm diameter) and ½" (98 mm length, 30 mm diameter) at different openings of the valve. The available data from manufacturer regard only the overall noise reduction in dB(A) without information about the spectral reduction (for example, in case of the Atomuffler the available datasheets give an average noise decrease of 17 dB to 25 dB, and a maximum of 37 dB). The quality of each single silencer is in our case evaluated through the difference between the spectra of the noise before and after the insertion of the device.

For a comparative evaluation of the attenuation efficiency of the devices, Figure 13 shows the trends of the difference between the values of the spectral levels obtained without silencers and those with the silencers on, with valve opening equal to 100%

With regard to the Atomuffler, the attenuation efficiency of the device for frequencies above 1000 Hz, is higher than

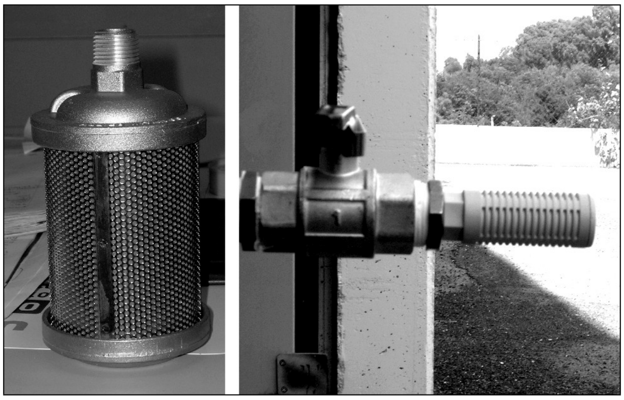

Figure 12. The silencer in test: Atomuffler (at left) and SMC (at right).

that found in the hyperbaric chamber (Figure 9), which was the subject of previous assessments. This suggests the possible presence, inside the chamber, of noise sources other than aerodynamic ones due to the air jets output (distributed along the chamber and on which the silencers directly intervene); they may be due for example to induced vibration of the delivery manifold and caused by the air flow through the valve. That may be also validated by the fluctuations of the spectral response in the experiments performed within the chamber, that are presumably due to resonance conditions of various objects and structures inside of it. From the spectral differences of Figure 13 it is evident that the silencer SMC ½" is the most effective in reducing the level of noise, while the SMC 1" and the Atomuffler perform quite similar. To better detail the comparison, other noise measurements were carried out at various flow conditions corresponding to different degrees of opening of the discharge valve. Figure 14 shows the third octave band spectra of the noise attenuation produced by silencers SMC ½" and Atomuffler, for the opening degree of valve equal to 100% and 50%: the noise reduction is slightly higher for the larger degree of the valve opening, because the reduction of the air flow rate produced by the inserted silencer is, as expected, more effective at higher flow rate values than at lower ones.

The decrease of noise obtained by silencer SMC, potentially candidate for use in the hyperbaric chamber, with respect to the device currently employed, is always greater in the range of frequencies above 400 Hz for all the flow configurations considered, confirming the better performance of the SMC model. However, the best use of silencer should always be undertaken by considering the overall acoustic performance of the chamber; particularly, the effect of possible alternative routes of noise entrance into the chamber from air supplying tubes, as it has been previously put in evidence.

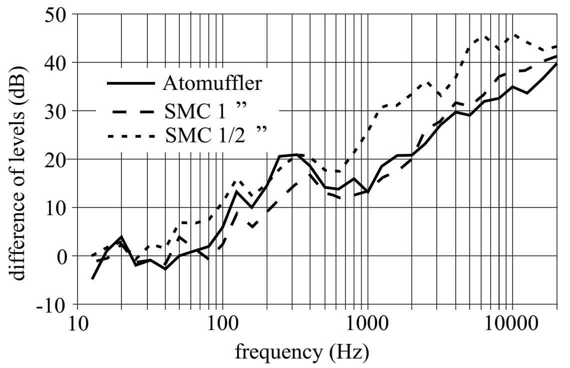

Figure 13. Attenuation effect of different silencers: differences in frequency spectra of sound pressure level with and without silencers in case of full opening of the valve.

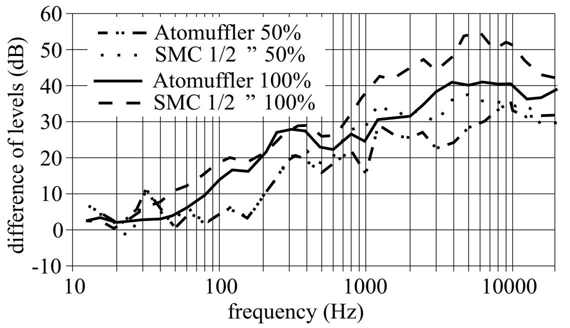

Figure 14. Noise attenuation due to SMC ½" and Atomuffler: frequency spectra at two different opening values of the valve.

4. Conclusions

The attenuation of the aerodynamic noise generated inside hyperbaric chambers, in particular in the chamber installed at Hyperbaric Therapy Center of Policlinico Umberto I in Rome, due to the air stream used to pressurize the chamber, is generally obtained through installation of silencers at the air outlets.

In this paper we present a series of measurements of noise, carried out in the chamber, under various conditions of opening degree of the air inlet valve, with or without silencers on the air outlet openings and with or without the pavement structures. From preliminary remarks, we can say that the silencers do contribute most significantly to noise reduction, although damping effect on the wind noise is also performed by the metal floor. Limitation to the attenuation produced by the various elements is due to the resonance of silencers and / or the floor at specific frequencies. The experimental results suggest that the optimization of some of the flow parameters and operating conditions of the chamber can significantly contribute to noise reduction and to a consequent improvement of this device, particularly in emergency conditions.

In this work a series is also presented of noise measurements carried out in the open field during the evacuation of a pressurized tank, in various conditions of opening of the discharge valve, for different types of silencers placed on the outlet. The analysis of the obtained frequency spectra allowed a preliminary assessment of the behavior of these devices and the identification of the silencer potential candidate for the use in the hyperbaric chamber under investigation. The choice of attenuation devices must be carefully assessed in relation to the strict rules and safety regulations.

The different effectiveness of the device Atomuffler obtained in the open field compared to that found in the hyperbaric chamber makes it presumable that other sources of induced noise are present, in addition to the air jets output (distributed along the chamber and on which silencers directly intervene); they may be due for example to induced vibration of the delivery manifold and caused by the air flow through the valve. This would make the silencers only a part of the solution, and would then require further investigation within the chamber. In particular, attention must be paid to the aerodynamic noise generated at the supply valve located upstream of the air outlet vents, evaluating the effects of a silencer dedicated to it.

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