14th ICBEN 2023
18 - 22 JUNE
BELGRADE

14th ICBEN Congress on Noise as a Public Health Problem

Occupational exposure to ultrasound generated by cleaners

Raffaele Mariconte[1], **Diego Annesi**[2], **Paolo Lenzuni**[3]

[1] Italian National Institute for Insurance against Accidents at Work, Dept. of Technological Innovation, Rome, Italy
[2] Italian National Institute for Insurance against Accidents at Work, Dept. of Occupational Medicine and Hygiene, Rome, Italy
[3] Italian National Institute for Insurance against Accidents at Work, Tuscany Regional Research Center, Florence, Italy

Corresponding author's e-mail address: p.lenzuni@inail.it

ABSTRACT

Italian legislation identifies ultrasound as one of the officially recognized physical risk factors. As such, it mandates that risks associated to exposure to ultrasound are evaluated and assessed. However, it does not clarify which descriptor should be used in the evaluation and assessment procedure. Nor does it indicate if only auditory risks should be considered (in analogy to noise, where quoted limits are clearly aimed at preventing the occurrence of hearing deficits) or non-auditory risks as well. Evidence indicating hearing impairment due to exposure to ultrasound is minimal, if any. Therefore, in this paper we support the adoption of a descriptor tailored for non-auditory effects. Unlike auditory risks, which are mostly linked to a long-term integration of the exposure energy, non-auditory risks involve short-timescale reaction mechanisms by the human body. In addition, ultrasound has often a markedly impulsive nature, so that the ideal descriptor should also be sensitive to quick acoustic pressure ramps. We identify the largest of the slow-weighted levels of the entire exposure as the best suited descriptor. A procedure that leads to its unambiguous estimate is outlined, which makes use of statistical inference techniques in case the exposure is only partially sampled. We then proceed to apply this procedure to the specific case of ultrasonic cleaners, which likely represent the single most common source of occupational exposure to ultrasound. Results indicate that the exposure remains well below the limits of acceptability, provided that the operator’s head is adequately positioned with respect to the ultrasonic source. In particular, positioning the head directly above the cleaner should be avoided. Once this basic prevention actions are taken, ultrasonic cleaners can be safely operated without hearing protectors, thus significantly contributing to the workers’ overall comfort and wellbeing.

Keywords: Ultrasound, exposure, descriptor, cleaners

INTRODUCTION

Auditory and non-auditory effects

Despite the fact that Italian legislation includes ultrasound in the list of bona-fide physical risk factors at the workplace, their evaluation and assessment is occasional at best. This may be due to the limited number of subjects professionally exposed to ultrasound (roughly estimated between 50 and 100 thousand), which makes employers and occupational hygienists alike unfamiliar with this type of investigation. A strong contribution to this negligence also comes from the absence of technical standards and even technical recommendations indicating which quantity should be used as the descriptor of exposure and how this quantity should be best estimated.

To make things worse, there is a lingering debate between two conflicting viewpoints on what the object of the assessment should be: some suggest that only auditory risks should be assessed, similarly to what occurs for "ordinary" noise, while others would also consider non-auditory risks. Despite decades of investigations dating back to the late 1940's[1,2], unambiguous evidence of hearing deficits or impairments due to prolonged exposure to ultrasound is extremely weak, and possibly altogether absent, unless extremely high levels are considered[3]. Much more sizeable[4] is the amount of evidence indicating non-auditory effects with symptoms that include dizziness, balance disturbances, headache, tinnitus and fatigue. These symptoms are often handled as specific elements of a more general conceptual category identified as annoyance or discomfort. They all contribute to worsen the quality of life and also interfere with work activities.

Experimental data on non-auditory effects is all concentrated in the low-frequency range (below 50 kHz) of air-borne ultrasound[4]. While the perception mechanisms of these acoustic waves is still controversial[5], the existence of adverse effects is proven beyond doubt.

In this work we proceed with a threefold objective:

a) we first identify the acoustic quantity that is best suited for the assessment of discomfort/annoyance caused by air-borne ultrasound;
b) we then develop an experimental procedure to more precisely estimate this quantity;
c) finally, we evaluate and assess the exposure for the case of ultrasonic cleaners.

MATERIALS AND METHODS

Historical Background

Far from being the end result of prolonged exposure, discomfort due to ultrasound is usually the outcome of a sequence of exposures extending over limited or very limited timescales, in similar fashion to other kinds of discomfort deriving from exposure to non-ideal temperature, noise, vibration, air quality and illumination. This implies that the descriptor of discomfort should also be characterized by a short and clearly identified integration timescale. This apparently trivial fact has only recently been recognized and incorporated in technical documents. A notable case is that of the German standard VDI 3766[6] which advocates the use of the largest of the 5-minute short-L_{eq} in each ultrasonic one-third octave band. While such an approach recognizes the importance of a well-defined short-timescale descriptor, it still fails to take into account the role of the possible impulsive nature of the exposure. In this perspective, a more appealing approach comes from the polish legislation with associated technical documentation: alongside with a long-timescale 8-hour integrated descriptor that is conceptually identical to the daily exposure to noise, a much more discomfort-oriented very short-timescale descriptor is also included. This was originally[7] only vaguely indicated as "the largest level of ultrasonic pressure" leaving very wide margins of interpretation. It has then been more precisely[8] identified with the maximum slow-weighted level in each ultrasonic one-third octave band between 10 and 40 kHz.

Identification of the descriptor

The procedure adopted by polish researchers requires that the previously quoted "maximum slow-weighted level" is very simply estimated as the "the greatest value obtained during the measurements"[9]. While this purely experimental determination is free of any uncertainty associated to the selection of a specific inferential procedure, it ignores the impact of finite sampling. In analogy to occupational exposure to noise, occupational exposure to ultrasound is typically evaluated from just a few short measurements (5 minutes or possibly less, see ISO 9612[10]). While this action plan does not introduce any bias in the estimation of the mean level, and is therefore a suitable strategy to estimate the equivalent continuous sound/ultrasound pressure level L_{eq}, the same does not apply to the estimate of the "greatest value". Taking just a few short measurements would be tempting for those who wish to have as low a result as possible, since the largest measured value increases (or at least it does not decrease) when the total measurement time increases. In order to eliminate any shortcut of this kind, we identify the optimal descriptor with the largest of all the slow-weighted values occurring during the entire exposure ($L_{Smax,E}$). This quantity is unambiguously defined, and it can be unambiguously estimated.

Experimental campaign

Two ultrasonic cleaners were tested in the laboratories of the Italian National Institute for Insurance against Accidents at Work (INAIL) located in Monteporzio Catone, near Rome. A first set of measurements was carried out in the fully anechoic chamber using the Elma Transonic cleaner. A total of 13 measurements were performed at 1 m from the source, orienting the microphone as follows:

- $\theta = 0°$, $\phi = 0°$ to 315° at 45° intervals, for a total of 8 measurements;
- $\theta = 45°$, $\phi = 0°$ to 270° at 90° intervals, for a total of 4 measurements;
- $\theta = 90°$, 1 measurement,

where θ is longitude, ϕ is latitude. The $\theta = 0°$ reference direction was set with the microphone facing the long side of the cleaner that includes the timer (see Figure 1). This first set of measurements was aimed at designing the 3D ultrasound emission pattern of the cleaner.

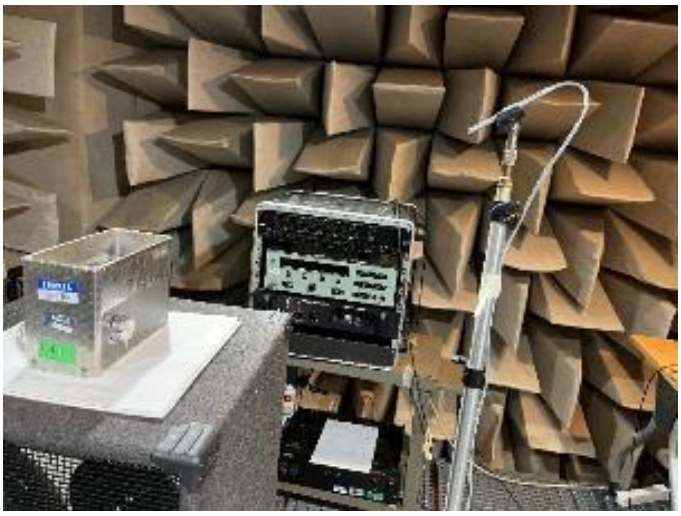

Figure 1 – Measurement set up. The configuration shown is $\theta = 45°$, $\phi = 0°$

A second set of measurements was carried out using the Branson 2510 cleaner in the chemistry laboratory, an environment where ultrasonic cleaners are routinely used. Three sequential measurements were made for a total duration of about 200 minutes,

corresponding to the full daily duration of the exposure. Microphone positions and orientations were chosen in such a way to replicate the most common positions and lines of sight of the operator during the day. This second set of measurements was aimed at estimating the actual exposure of the operator.
All measurements were carried out using a Brüel & Kjær Type 4941 1/4” microphone, and a Sinus Soundbook analyzer.

RESULTS

Emission pattern

Figure 2 shows the ultrasonic one-third octave band spectrum of the Elma cleaner, in the range 10 to 80 kHz (band center). Panel a) on the left shows the ultrasonic levels measured for eight azimuthal angles (0° to 315° with 45° steps) in the horizontal plane $\theta = 0°$. Panel b) on the right shows the ultrasonic levels for two angles of latitude ($\theta = 45°, 90°$). Regardless of the emission angle in space, the largest ultrasonic levels are always found in the one-third octave band centered at 40 kHz. Therefore, the 40 kHz one-third octave band level is the one to be checked against exposure limits, in order to ensure that compliance exists.

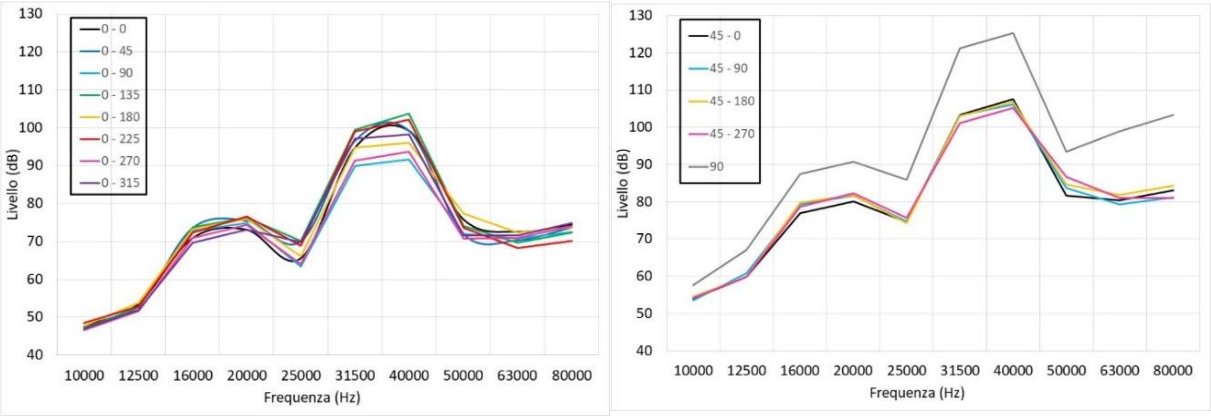

Figure 2 – Emission spectra of the Elma ultrasonic cleaner. a) Horizontal plane, $\theta = 0°$ (left panel); b) $\theta = 45°$ and $\theta = 90°$ (right panel)

Figure 2a shows that there is a small but non negligible fluctuation of the emission in the horizontal plane. The effect of the angular distance from the horizontal plane can be seen to stay moderate up to 45° (Figure 2b), becoming extremely large for near vertical directions (about 20 dB for $\theta = 90°$). These results indicate that careful microphone positioning is of primary importance. It also suggests that the operator should refrain from operating the device from the above, a likely possibility if “checking what’s going on” is requested.

Actual exposure

Figure 3 shows the time history of slow-weighted ultrasonic levels measured in the 40 kHz one-third octave band, previously identified as the band with the highest emission level. About 12000 samples were collected (one every second).
Because in this case the total duration of measurements is equal to the actual exposure duration, the true value of the largest slow-weighted ultrasonic pressure level of the entire exposure can be experimentally determined. This value shall be identified with the symbol $L_{Smax,E\text{-}true}$ and its value is 111.1 dB. Existing limits of acceptability for the maximum slow-weighted level are summarized in Table 1, taken from the work by Pleban et al.[9]. It is easy to see that $L_{Smax,E\text{-}true}$ is almost 20 dB below the limit of acceptability at 40 kHz.

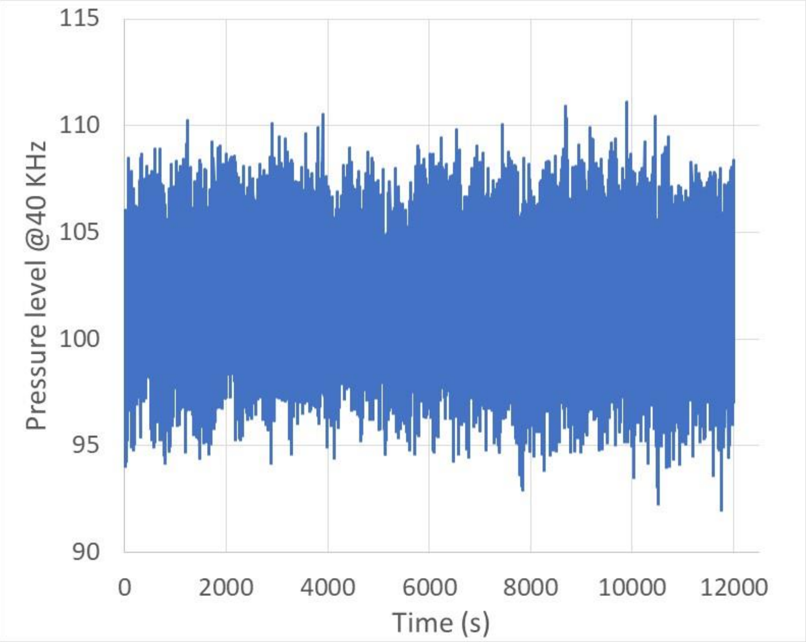

Figure 3 – Time history (slow-weighted) of 40 kHz ultrasonic levels

Table 1– Limits of acceptability on the largest slow-weighted ultrasonic level

Band center (kHz)	**Limit (dB)**
10 – 12.5 – 16	100
20	110
25	125
31.5 – 40	130

DISCUSSION

Statistical estimation of $L_{Smax,E}$

Generally speaking, the time evolution of the ultrasonic emission of any device may belong to one of two classes, depending on the operating mode of the source.

In class 1, the emission is dominated by strong peaks occurring each time the device is switched on. This case is identified as “non-stationary”. The relevant values for exposure quantification are only those occurring during the switch-on events. Accordingly, the total population to be analyzed has consistency $N = N_{sw}$ where N_{sw} is the total number of times the device is switched-on during the day. Because N_{sw} is presumably a small number, the largest slow-weighted value L_{Smax-i} associated to the i^{th} event can be measured, and a “direct” estimate of the largest value of the entire exposure $L_{Smax,E}$ can be found. No statistical inference methods are needed and the final result is simply

$$L_{Smax,E} = \max (L_{SMax-i}) \quad \text{for } i = 1 \text{ to } N \qquad (1)$$

In class 2, the emission shows no large dependence on the device operating phase. This case is identified as stationary. All the slow-weighted levels occurring during the entire exposure are equally relevant. The size of the population to be analyzed is then $N = T_{exp}/T_{meas}$, where

- T_{exp} is the total exposure time;
- T_{meas} is the (average) duration of each individual measurement.

Because T_{exp} can be quite long (several tens of minutes to hours) while T_{meas} is usually of order a few minutes (see the previous section), N is now presumably large, and an “indirect” estimate of the exposure largest value $L_{Smax,E}$ becomes unavoidable. This requires that a statistical inference procedure is set up. Here we use a simplified version of the procedure originally developed[11] for estimating the peak sound pressure level for occupational exposure to noise.

The largest of the N members of a population can be estimated as the quantile q of the distribution such that there is a 50% probability that none of the N members is positioned beyond q

$$(1 - q)^N = 0.5 \qquad (2)$$

Upon inverting equation (2), an explicit expression for q can be found

$$q = 1 - 0.5^{1/N} \qquad (3)$$

Unless detailed information exists indicating an asymmetric distribution, it shall be assumed that the largest slow-weighted values of each measurement (L_{Smax}) are normally distributed. The exposure descriptor $L_{Smax,E}$ can accordingly be estimated as

$$L_{Smax,E} = L_{Smax,m} + z(0.5^{1/N})\, \sigma(L_{Smax}) \qquad (4)$$

where

- $L_{Smax,m}$ is the arithmetic mean of the values L_{Smax} resulting from the measurements randomly carried out during the exposure;
- $\sigma(L_{Smax})$ is the standard deviation of the values L_{Smax} resulting from the measurements randomly carried out during the exposure;
- z is the cumulative function of a standardized (mean = 0, standard deviation = 1) normal distribution.

The case of ultrasonic cleaners

In order to simulate the measurements that would be taken during a real procedure of evaluation and assessment of exposure to ultrasound, six 4-minute long samples were randomly extracted from the 200-minute long measurement performed in the chemical laboratory. Table 2 synthesizes the maximum slow-weighted levels L_{Smax-i} (i = 1 to 6) obtained in the measurements, in each of the one-third octave bands between 10 and 80 kHz.

Table 2 – Maximum slow weighted values obtained in individual 4-minute samples

Band	**L_{Smax-1}**	**L_{Smax-2}**	**L_{Smax-3}**	**L_{Smax-4}**	**L_{Smax-5}**	**L_{Smax-6}**
	(dB)	**(dB)**	**(dB)**	**(dB)**	**(dB)**	**(dB)**
10 kHz	73.92	73.00	73.72	73.18	72.91	72.97
12.5 kHz	76.30	76.06	76.22	75.57	75.37	75.02
16 kHz	81.26	81.77	80.93	80.67	81.42	81.26
20 kHz	86.00	88.07	85.68	85.30	89.48	88.52
25 kHz	82.24	81.12	81.00	80.33	80.42	80.58
31.5 kHz	96.20	96.39	96.05	98.49	99.26	96.89
40 kHz	108.46	108.91	109.25	109.48	109.90	107.84
50 kHz	81.03	82.37	81.34	81.87	83.59	83.71
63 kHz	78.01	78.64	78.21	78.40	79.85	80.37
80 kHz	83.62	83.84	84.92	85.41	84.23	85.53

Because each sample has a duration T_{meas} = 4 minutes, and the total exposure time is 200 minutes, the total size of the population under investigation is $N = T_{exp}/T_{meas} = 200/4 = 50$, which implies $z(0.5^{1/50}) = 2.204$. Table 3 summarizes the values of all the relevant quantities for the calculation of the statistically inferred largest slow-weighted value of the exposure, here indicated with the symbol $L_{Smax,stat}$. Table 3 shows that the simple statistical inference procedure outlined in this work (column 4) gives a slight underestimate of about -0.5 dB in the 40 kHz one-third octave band. On the opposite, adopting the largest measured value (109.9 dB, in measurement #5, see Table 2) would result in an underestimate of 1.2 dB. Even larger underestimates would occur if fewer measurements were taken.

Table 3 – Statistical estimates and actually measured values of largest slow-weighted levels

Band	**L_{Smax-m}**	**$\sigma(L_{Smax})$**	**$L_{Smax,E-stat}$**	**$L_{Smax,E-true}$**	**Difference**
	(dB)	**(dB)**	**(dB)**	**(dB)**	**(dB)**
10 kHz	73.28	0.43	74.22	74.79	-0.57
12.5 kHz	75.76	0.52	76.89	76.44	0.45
16 kHz	81.22	0.38	82.07	81.77	0.29
20 kHz	87.17	1.74	91.00	89.82	1.18
25 kHz	80.95	0.71	82.51	82.24	0.27
31.5 kHz	97.21	1.34	100.16	99.57	0.59
40 kHz	**108.97**	**0.74**	**110.60**	**111.13**	**-0.53**
50 kHz	82.32	1.13	84.81	83.70	1.10
63 kHz	78.91	0.96	81.04	80.65	0.39
80 kHz	84.59	0.81	86.38	86.32	0.06
Arithmetic mean					+0.32
Standard deviation					0.58

The same calculation has been replicated in the other one-third octave bands, resulting in differences between the statistical estimates and the corresponding "true" measured values ranging between -0.57 dB and +1.18 dB, with mean +0.32 dB and standard deviation 0.58 dB. In consideration of the uncertainties due to the finite sampling, to microphone position and orientation, and to instrumentation[12], this result is unlikely to significantly contribute to the total uncertainty on the descriptor, and as such it is deemed acceptable.

CONCLUSIONS

Unlike noise, which is a consolidated physical risk factor, and for which prevention of auditory risks is the primary objective of the assessment, ultrasound is mostly a discomfort factor. Accordingly, any assessment of exposure to ultrasound should be primarily targeted at minimizing non-auditory effects.

Because discomfort develops over short timescales (minutes), a short-timescale descriptor should be adopted. While alternative proposal have been made in technical standards, in this paper we follow the line set by polish researchers and advocate the use of the largest of all the slow-weighted ultrasound pressure levels during the exposure, $L_{Smax,E}$. However, we argue that the purely metrological approach that takes the largest of the measured values, leads to a systematical underestimate of the descriptor. A much more reliable estimate can be obtained by adopting an indirect approach that relies on statistical inference. Results indicate that the statistical procedure manages to accurately predict the largest slow-weighted values of the exposure in all ultrasonic one-third octave bands. In an experimental campaign on ultrasonic cleaners, we find a mean error of order 0.3 dB.

The largest ultrasonic levels emitted by ultrasonic cleaners occur in the 40 kHz one-third octave band, so this is where results should be checked against limits of acceptability. The largest slow-weighted level of the exposure (either measured, 111.1 dB or estimated, 110.6 dB) is almost 20 dB below the current limit of acceptability in this band (130 dB). This implies that ultrasonic cleaners, if correctly operated, do not create discomfort and do not lead to non-auditory effects.

Acknowledgements

We wish to thank Lucia Rocca Mainero and Andrea Gordiani for kindly providing access to the chemistry lab of the INAIL research center, where some of the experiments were carried out.

REFERENCES

[1] Allen CH, Rudnik I, Frings H. Some biological effects of intense high frequency airborne sound, J Acoust Soc Am 1948; 20(1): 62-65.

[2] Davis H. Biological and psychological effects of ultrasonic. J Acoust Soc Am 1948; 20(5): 605-607.

[3] Parrack HO. Effects of airborne ultrasound, Int Aud 1966; 5: 294-308.

[4] Smagowska B, Pawlaczyk-Łuszczyńska M. Effects of Ultrasonic Noise on the Human Body - A Bibliographic Review, International Journal of Occupational Safety and Ergonomics (JOSE) 2013; 19(2): 195-202.

[5] Nishimura T, Okayasu T, Yamashita A, Hosoi H, Kitahara T. Perception Mechanism of Bone-Conducted Ultrasound and Its Clinical Use, Audiology Research 2021; 11: 244-253.

[6] VDI 3766:2012, Ultrasound - Workplace - Measurement, assessment, judgement and reduction, Verein Deutscher Ingenieure, Germany.

[7] Announcement of Minister of Family, Labour and Social Policy of Poland (2018), Regulation of the Minister of Family, Labour and Social Policy of 12 June 2018 on the maximum permissible concentrations and intensities of factors harmful to health in the working environment, Journal of Laws 2018, item 1286.

[8] Pawlaczyk-Łuszczyńska M, Dudarewicz A, Śliwińska-Kowalska M. Theoretical Predictions and Actual Hearing Threshold Levels in Workers Exposed to Ultrasonic Noise of Impulsive Character – A Pilot Study, International Journal of Occupational Safety and Ergonomics (JOSE) 2007; 13(4): 409-418.

[9] Pleban D, Radosz J, Smagowska B. Assessment of Occupational Risk in the Case of the Ultrasonic Noise Exposure, Archives of Acoustics 2021; 46(1):167-175.

[10] ISO 9612:2009, Acoustics - Determination of occupational noise exposure - Engineering method.

[11] Lenzuni P. Application of the Extreme Value Distribution to Estimate the Uncertainty of Peak Sound Pressure Levels at the Workplace, Ann Occup Hyg 2015; 59(6): 775-787.

[12] Radosz J. Chapter 8 – Ultrasonic noise measurements in the work environment. In: Pleban D, editor. Occupational Noise and Workplace Acoustics. CRC Press, Taylor and Francis Group; 2021. pp 221-251.