THE EUROPEAN SOCIETY OF MEDICINE
Medical Research Archives, Volume 14 Issue 5

RESEARCH ARTICLE

Infrasonic Noise Exposure: How Outdated Noise Legislation Misinforms Medical Communities Perpetuating Grave Misconceptions About Noise Doses

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OPEN ACCESS

PUBLISHED
31 May 2026

CITATION
Pereira-Sousa, P., Bakker, HHC., et al., 2026. Infrasonic Noise Exposure: How Outdated Noise Legislation Misinforms Medical Communities Perpetuating Grave Misconceptions About Noise Doses. Medical Research Archives, [online] 14(5).

ISSN
2375-1924

ABSTRACT

Background: Clinical practice among noise-exposed workers is mainly focused on monitoring patients' auditory acuity, mostly achieved through administering periodic audiograms, a practice adopted among EU-Member States. The dose-response relationship between noise levels and hearing impairment is well-established. Over the past 100 years, noise-protection has been, almost exclusively, equated with protection of the hearing function. This has diverted attention from the type of noise that does not necessarily cause hearing impairment (as measured through audiograms) but that can, nevertheless, impact workers' health. One of the most insurmountable obstacles to scientific advancement in this field is the deceptive and crude acoustic metrics provided to the medical community, purportedly representing the *noise dose* to which workers are exposed. This deception is incurred through noise assessment methodologies that are imposed by the legislative bodies, and which were designed and conceived almost 100 years ago. Modern, scientific-grade characterizations of acoustic environments, however, could be providing a much deeper understanding of the signs and symptoms observed in noise-exposed workers.

Aim: To bring awareness to the medical community on how it is being greatly misled as to the real, physical dose of noise exposure of workers under their care.

Methods: Full-spectral (0.5 Hz–20 kHz) recordings were taken in several workplaces using the SAM Scribe system. Continuous recordings captured during several days were analyzed in the 0.5–1000 Hz region, using a 1/36 octave spectral resolution (instead of the imposed 1/3 octave), a temporal resolution of 1-second (instead of the imposed 10-minutes), and no frequency-weighting, i.e., sound pressure levels (SPLs) expressed in dBZ.

Results: One industry (8 workstations) was selected as an example to compare data obtained with imposed methodologies, with that obtained with more modern technologies. A- and G-weighted SPLs prove to be insufficient to characterize the dose of noise to which workers are exposed. New visual formats for evaluating noise exposures have been developed to better aid the clinician.

Conclusion: The outdated, but legally binding, methodologies used to measure noise deceive the medical community as to the dose of noise to which workers under their care are physically exposed. A serious adjustment is urgently required.

Keywords: Infrasound, low frequency noise, A-weighting, Z-weighting, G-weighting, SAM Scribe

1. Introduction

1.1 THE CURRENT STATUS QUO IN EU-MEMBER STATES

Protection against the risks associated with noise exposures among workers is often thought to be a 'done deal.' Periodic audiometric monitoring is generally considered to be satisfactory to protect against hearing loss. Personal protection equipment is also widely used among workers exposed to sound pressure levels (SPLs) above 80 dBA. In the more severe cases, noise reduction at the source is implemented through the introduction of shock absorbers, insulation materials, acoustic barriers and other strategies. Changes in work-shifts can also be implemented to reduce the period of time workers are exposed to the aggressive noise environments. Additionally, noise-exposed workers are usually afforded training and educational programs to increase their awareness of the dangers of noise-induced hearing loss and to understand how to properly use the relevant personal protection equipment. The Dose-Response relationship for noise exposure and hearing loss, defined many decades ago, is the basis for the noise protection legislation adopted in the EU,[1] a brief example of which is provided in Table 1.

Table 1. Permissible exposure levels for occupational noise in EU-Member States.[2]

	8-hour exposures	**Peak**
Maximum exposure limit	87 dBA	140 dBC (200 Pa)
Upper action value	85 dBA	137 dBC (140 Pa)
Lower action value	80 dBA	135 dBC (112 Pa)

* Action values are those at which the employer is required to implement Adequate preventive measures to reduce the risk to workers' health.

What do these numbers actually mean? What kind of units are dBA and dBC? Why is the medical community led to believe that these numbers fully protect workers against noise exposures? Mostly the reasons are historical, stemming from an era when sound measuring instrumentation was very limited, sophisticated analysis was too computationally expensive, and when noise was only considered harmful if it could be heard, i.e. "*what you can't hear, can't hurt you.*"

1.2 THE BASIS FOR CURRENT LEGISLATION

The Dose-Response values for the human hearing threshold were first established by the Fletcher and Munson curves in 1933,[3] within the scope of the development of the telephone. The relevant International Standards Organization (ISO) document—ISO 226:2023-3–*Acoustics: Normal equal-loudness-level contours*[4]—stems from these curves. The Fletcher-Munson curves are also the basis for the A-frequency weighting filter (or A-weighting), which today is commonly applied to practically all noise assessments. A-weighted SPLs measure the acoustic environment as it is *heard* by humans. Its use was, and is, appropriate for preventing hearing loss. Regrettably, though, this is oftentimes the only type of noise-dose data presented to clinicians. Figure 1 shows how the application of A-weighting cannot be used to distinguish between two significantly different acoustic environments.

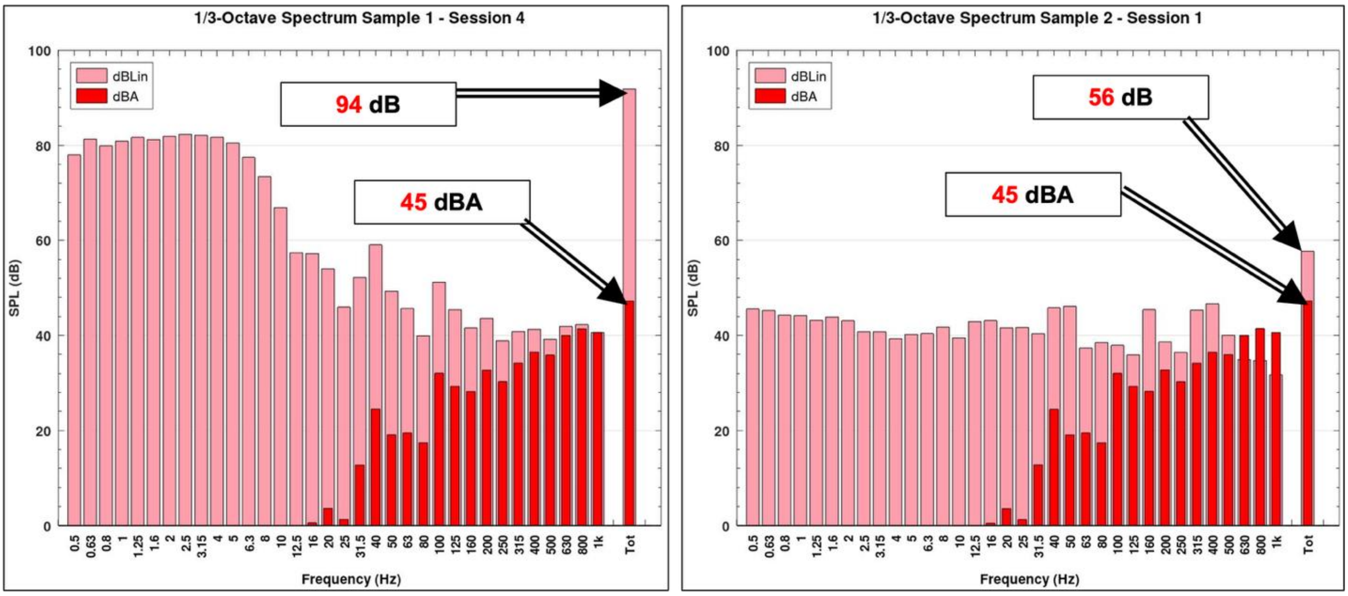

Figure 1. Frequency distribution analyses of two acoustic environments, represented as 10-minute averages with spectral resolution of 1/3 octave, as required by legislation. The application of A-weighting (red bars) means that only the 'audible portion of the acoustic spectrum is evaluated. In both these samples, the A-weighted value is 45 dBA. However, removal of the A-weighting methodology (linear assessment-pink bars) discloses samples with 94 dB and 56 dB. While these two samples may be acoustically equivalent in the classical audible range (using A-weighting), they are far from being comparable in terms of noise-dose (field-data from Paint Factory Recording Sessions Nos. 1 and 4, see text). (Note: Unweighted sound pressure levels are expressed in dBLin or dB)

The widely adopted values presented in Table 1 should, for the medical community, now take on a different look. Exposure to 80 dBA and above (for 8-hour exposures) means there is a risk of hearing loss. Is that the *only risk* that a worker might undergo when working in these acoustic conditions?

1.3 CONSEQUENCES OF A MISLEADING NOISE DOSE

The dose refers to the amount of the agent of disease to which a person is exposed until a certain response is observed. For example, how much (*dose*) organic mercury must be ingested before numbness around the mouth (*response*) is felt? In occupational environments, this dose does not exclusively refer to the actual physical quantity of the agent of a single exposure, but also to the time over which exposure to that agent occurs. For example, the dose of radiation received during a single x-ray examination is considered harmless. But if that same x-ray were received 5 times daily over a period of three years, the cumulative effects may not be considered so harmless. Dose evaluates 'how much' during 'how long a period of time,' especially so within occupational settings. The *Dose-Response* relationship is key to Medical Sciences. The act of measuring noise is the moment in which the *amount of Dose* of the agent of disease is quantified. In the case of noise exposures, clinicians are being offered a single, A-weighted numerical value to characterize the *dose* of the agent of disease of their noise-exposed workers. As is clearly shown in Figure 1, the A-weighted numerical value merely quantifies the dose that is associated with a specific *Response—hearing impairment*, nothing more. More importantly, the A-weighted numerical values cannot properly distinguish between two very different acoustic environments, as clearly shown in Figure 1. This is where the very real possibility of misdiagnoses emerges.

A not-so-hypothetical example of a clinical situation using Figure 1 as reference:

Worker A is exposed to the environment shown in Sample 1—45 dBA

Worker B is exposed to the environment shown in Sample 2—45 dBA.

Workers A and B spend approximately the same amount of time in these occupational environments over their work-shifts. The operational tasks of Worker A and Worker B are comparable, as are their educational levels, age, body-type, familial and socio-economic backgrounds, and prior noise-exposure histories. Audiograms present values within normal limits, and no pre-existing medical conditions are known to exist.

Worker A presents with headaches, dizziness, knee pain, rapid decrease in visual acuity and increased irritability.

Worker B reports no complaints.

Is it, then, the hypothesis that the symptoms in Worker A *cannot* be caused by the noise environment, because otherwise Worker B would also exhibit some of the same symptoms? They are, after all, exposed to the *same noise dose* (45 dBA), are they not? Under these circumstances, the noise environment is usually *precluded from the hypothesis* of being the cause of Worker A's symptoms. In reality, however, Worker A is exposed to 94 dB while Worker B is exposed to 56 dB—A-weighted values are misleading as they exclusively only report the dose that is associated with noise-induced hearing loss—nothing else. The non-A-weighted numerical values of the acoustic environments constitute additional information on the *noise dose* which should be made available to clinicians; Or rather, that clinicians should be sufficiently cognizant to request.

1.4 INFRASONIC EXPOSURES: NOISE OR VIBRATION OR BOTH?

The *International Classification of Diseases* (ICD) is published by the World Health Organization (WHO) and assigns codes to medical ailments, procedures and situations.[6] The ICD-10 is being updated to another ICD-11 version. In this report, information from both ICDs, relevant to the matter at hand, will be examined.

In the ICD-10, the Chapter called "External Causes of Morbidity and Mortality" (codes V01 to Y98), includes the Section titled *Exposure to Inanimate Mechanical Forces* (codes W20-W49) (see Figure 2). "Exposure to Noise" and "Exposure to Vibration" (codes W42 and W43, respectively) fall under this Section. *Exposure to Noise* includes "sound waves" and "supersonic waves", while *Exposure to Vibration* includes "infrasound waves" [sic].

Chapter XX
External causes of morbidity and mortality
(V01-Y98)

Exposure to inanimate mechanical forces (W20-W49)

W42	**Exposure to noise**	
	Incl.:	sound waves supersonic waves
W43	**Exposure to vibration**	
	Incl.:	infrasound waves

Figure 2. Adapted from ICD-10[7]

At first glance, this may seem incongruous because *infrasound*, usually assessed with microphones, is normally relegated to the realm of noise and acoustics; while vibration, assessed with accelerometers, is usually associated with the existence of vibrating machines or platforms, with which the worker is in physical contact. In the ICD-10, these concepts appear to be intertwined. Exposure to infrasonic events is classified under Exposure to Vibration, rather than Exposure to Noise, as would initially be expected. This is reiterated by the classification of the medical condition *Vertigo from infrasound* under "Effects of vibration" (Code T75.2).

The ICD-11, organized in a different manner (see Figure), describes the circumstances of the injury rather than its physical origin. The intertwining of vibration and infrasound however is still present in the ICD-11. The only recognized effect caused by infrasound—vertigo (code

NF08.2Y)—falls under "*Other specified effects of vibration*" (see Figure).

NF08.2Y Other specified effects of vibration

Matching Terms

Vertigo from vibration
Vertigo from infrasound

Figure 3. Adapted from ICD-11[9]

This is not, perhaps, what is taught to the medical community, to industrial hygienists nor to safety & health in the workplace professionals. It is also quite a conundrum! How to prove exposure to infrasonic waves with vibration measurements? Is this not what is being required by the ICD? In fact, legislation, standards, guidelines and good practices practically preclude this from ever being achieved. So why is this classified in this manner? Once again, the reasons may be historical, although perhaps, this time, the older methodology should have been maintained.

23 External causes of morbidity or mortality

- unintentional (i.e. accidental)
- intentional (i.e. deliberate):
- interpersonal (e.g. assault and homicide)
- self-harm (e.g. abuse of drugs and alcohol, self-mutilation, suicide)
- legal intervention (e.g. action by police or other law enforcement personnel)
- war, civil insurrection and disturbances (e.g. demonstrations and riots)
- undetermined intent

Figure 4. Adapted from ICD-11 [8]

In 1968, the Annual Progress Report on the US Military's Project Poorboy[10] included a summary of its findings on "Low Frequency Vibration" (Figure 5):

1. Infrasound does affect the human organism both psychologically and physiologically.
2. Frequencies in the area of resonance of human organs, 3-15 hertz, appear to be more critical than other segments of the infrasound region.
3. The distinction between low frequency sound and vibration is not clear.
4. There exists a paucity of documentary evidence about the effects of severe infrasound on the human organism.
5. That information which is available suggests that infrasound may have greater effectiveness as a weapon than ultrasound, which has been examined considerably on this premise.

Figure 5. Summary of findings under the heading "Low Frequency Vibration" as contained in the 1968 Annual Progress Report of Project Poorboy (Reproduced from[10]).

In 1972, Shoenberger[11] explained that there were <u>three</u> situations through which humans could be exposed to vibration:

> *First, vibration may be applied to the entire body surface through a vibrating medium in which the body is immersed.* ***An example of this is vibration caused by high intensity sound (or infrasound) transmitted through air or water.***
> *Second, particular body parts, such as the hands or feet, may be vibrated through direct contact with the handles or pedals of vibrating machines, vehicles, or hand-held power tools.*
> *Third, vibrations may be transmitted to the body as a whole through its supporting surface (i.e., the feet of a standing man, the buttocks of a seated man, or the supporting area of a reclining man) as a result of direct contact with a vibrating structure.*[11] *[emphasis added]*

The position taken by the authors of this report is that infrasound exposure is yet another form of exposure to vibration. It also seems to be the position taken by the ICD. In the case of this '*infrasonic vibration*,' there is no solid-to-solid contact between the vibrating machine or platform and the worker, as in the other two forms of vibration exposure. Instead, airborne pressure waves vibrate viscoelastic biological tissues (air-to-solid). Physical and numerical data on this type of infrasonic vibration is not easily obtained through commercially available accelerometers, which are mostly designed to measure energy transfers between solid objects. Hence, in this case, microphones are more appropriate to quantify airborne pressure variations, and therefore, to characterize the acoustic environment that generates infrasonic vibration. (This report does not cover infrasonic vibration where the medium is not air, or that is captured with hydrophones or micro-barometers.)

1.5 FREQUENCY-DEPENDENT BIOLOGICAL RESPONSES

Over the decades, many experiments have been conducted to investigate the vibrational resonance frequencies of the human body, a small sample of which is shown in Table 2.

Similarly, Table 3 shows a small sample of the biological responses documented when infrasound (or infrasonic vibration) was used as stimulus.

Table 2. Partial List of resonance frequencies for different areas of the human body exposed to low frequency vibration, and source of information.

Human Body	Vibration Frequency (Hz)	Scientific Reference
Vertical vibrations (standing)		
Body	4–5	Dieckmann, 1958[12]
Head	5 and 12	
Whole-Body	4–6	Coermann, 1962[13]
Whole-body	4–7.5	Edwards & Lange, 1964[14]
Vertical vibration (sitting)		
Whole-body	5	Guignard, 1959[15]
Horizontal vibration (sitting)		
Head	2	Dieckmann, 1958[12]
Whole-Body Head, Hip, Knee	1.5	Edwards & Lange, 1964[14]

Table 3. Partial List of biological responses for elicited by infrasound exposure, and source of information.

Biological Response	Frequency (Hz)	Source
Swollen mitochondria in cardiomyocytes	5	Pei *et al.* (2016)[16]
Significant ventricular myocardial fibrosis, significant decrease in cardiac connexin 43 (Cx43)	6.3–25	Antunes *et al.* (2013)[17]
Time-dependent expression of heat shock protein (HSP70)	8	Zhang *et al.* (2016)[18]
Decreased arterial diameter and capillary expansion, myocardial damage with death of myocardiocytes	10–15	Alexeev *et al.* (1983)[19]

These stimuli, *vibration* and *infrasound*, are today considered entirely distinct physical agents of disease. In this report, the biological responses from both stimuli will be merged as per the value of the frequency of the stimuli (as shown below in Table 6).

1.6 GOALS OF THIS REPORT

To make clinicians aware of their lack of knowledge regarding workers' noise exposures, imposed upon them by antiquated but legally binding noise evaluation methodologies, and to provide clinicians with more relevant information on the *noise doses* to which workers under their care are exposed.

2. Methods

2.1 BACKGROUND

The data presented here was collected within the scope of an ongoing research project in Portugal, approved by the Ethics Committee of the University of Porto, and with the purpose of assessing occupational noise exposures within the frequency ranges below ≤1000 Hz, including infrasound ≤20 Hz. The site selected for presentation in this report is a Paint Factory with international standing, that employs approximately 150 workers and is located on the outskirts of Lisbon.

The analysis software used on the data acquired in this study was developed for the International Acoustics Research Organization (IARO) by Astute Engineering Ltd (Palmerston North, New Zealand) as part of the Citizens' Science Initiative ACHE—Acoustic Characterization of Human Environments.[20]

2.2 EQUIPMENT

The SAM Scribe Full Spectrum (Model Mk2, Soundscape Analytics, Palmerston North, New Zealand)[21] is not a sound level meter but, rather, a recording device. It was developed as a scientific instrument for the ACHE Citizens' Science Initiative.[20] Sound level meters currently available on the market are unable to provide scientific-grade data within ranges below 500 Hz. Sound level meters limit acoustic assessments to octave or 1/3 octave spectral resolutions (3 data-points per octave). With the SAM Scribe system, acoustic environments are recorded with high-fidelity onto non-compressed .WAV files. SAM Scribe allows for continuous data acquisition of sound down to 0.1 Hz, for days, weeks or months. The system comes equipped with two channels (blue and red microphones) and provides sound data via USB to a Windows computer, with a sampling frequency of up to 44.1 kHz. The SAM Scribe System also includes a calibrator (Type I, 1000 Hz/94 dB tone) whose tone is recorded at the start of every recording. GPS information on location is also recorded in the file metadata with a corresponding digital signature. SAM Scribe comes equipped with two omnidirectional electret microphones (model EM246ASS'Y, Primomic, Tokyo Japan). The frequency response curve is practically linear in the 1–1000 Hz range (0.5–1000 Hz: ± 0.5 dB, 1–10 kHz: ± 2dB; 10–20 kHz: ± 4dB).[22] Each file, containing a 10-minute recording of the acoustic environment, is then processed using the analysis software developed for IARO and which entails 1/36-octave analyses (36 data points per octave instead of 3) and a temporal resolution of 1 second (above 2.5 Hz), rather than the legislated 10-minute averages.

2.3 MEASUREMENT PROTOCOL

Four Recording Sessions were obtained within the Paint Factory during 22 April to 12 May 2024, with a sampling frequency of 11.025 kHz. Microphone calibration was conducted at the beginning and end of each Recording Session. Each recording includes data from 2 microphones, placed at two different workstations and fitted with windshields. Table 4 summarizes microphone placement and recording details, and Figure 6 provides an example of microphone placement for Recording Session No. 4

Table 4. Summary of the four Recording Sessions conducted within the Paint Factory in 2024, including date, total number of hours recorded, and microphone placement in the 8 workstations.

No.	Date	No. hours/ No. 10-min files	Blue Microphone	Red Microphone
1	22 – 26 Apr	99.5/ 596	Quality control lab	Manufacturing area
2	26 Apr – 01 May	113.0/ 517	Filling unit office	Filling unit floor
3	03 – 10 May	167.3/ 933	Quality office	R&D* lab
4	10 – 12 May	49.8/ 296	Security office (outside)	Security office (inside)

* *Research and Development*

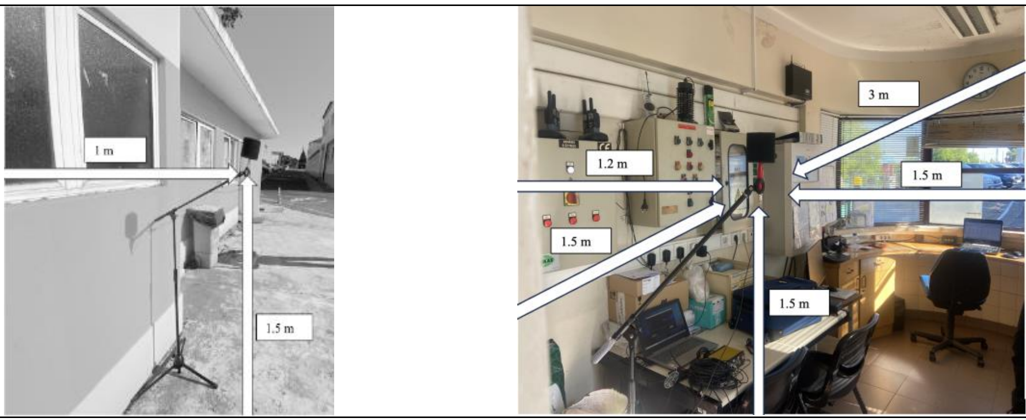

Figure 6. Example of microphone placement for Recording Session No. 4: outside and inside the Security Office. (Left image was cropped and kept in black and white to maintain anonymity.)

2.4 SEGMENTATION OF THE ACOUSTIC SPECTRUM

As discussed in Section 1.5, the segmentation of the acoustic spectrum used in this report amalgamates vibration and infrasound studies (Tables 2 and 3), rejecting the notion that infrasonic exposures fall exclusively under the category of 'noise exposure.' A sample of the data used for this new segmentation of the acoustic spectrum is shown in

Table 5.

In this present study, the biological response with varying SPLs at each frequency range is not covered in detail, although it is also the object of ongoing investigation. The focus herein is to develop an analysis technique, with clinical relevance, that can account for frequency variations. Accordingly, the spectral segmentations applied to the data collected in the Paint Factory are listed in Table 6.

Table 5. Examples of biological responses obtained with exposures of well determined frequencies, and reference to the scientific source of information.

Biological Response	Frequency (Hz)	Source
Body reacts as single mass	<2	Maritime Health Textbook, 2021[23]
Stomach	2–3	Gora *et al.*, 2020[24]
Abdomen and diaphragm	3–4	Ashe, 1961[25]
Thorax	3–7	Maritime Health Textbook, 2021[23]
Heart	4–8	Maritime Health Textbook, 2021[23]
Abdomen	4–8	FAO, 1992[26]
Swollen mitochondria in cardiomyocytes	5	Pei *et al.*, 2007[16]
Time-dependent expression of heat shock protein (HSP70)	8	Zhang *et al.*, 2013[18]

Table 6. Example of the segmentation of the acoustic spectrum from 0.5—7 Hz.

Spectral Region	Frequency Range (Hz)
1	0.5–2
2	2–4
3	3–7

3. Results

Acoustic environments can be studied as to their SPL values (with or without A-weighting). They can also be studied as to their time profile (how long are SPLs maintained at a particular value). And they can also be investigated as to the variation of SPLs throughout the different frequency ranges. All this information is relevant to establishing the (real) amount of workers' noise exposure.

3.1 CLASSICAL QUANTIFICATION OF SOUND PRESSURE LEVELS, EXPRESSED IN DBA AND DBZ

Classical evaluations using A-weighted values, averaged over each 10-minute recording, for each microphone, were computed for all 4 Recording Sessions and 8 workstations. The same was done for the Z-weighted values. A summary of these values for Recording Session 1 (which yielded 596 10-minute continuous recordings) is presented in Table 7, from which several observations can be pointed out.

In 59% of the recordings captured in the Quality Control Lab (Blue mic, see Table 4), A-weighted SPLs registered between 40–50 dBA. In the same recordings, 58% registered levels between 60–70 dBZ (no weighting). Within the Manufacturing Area, where the Red microphone was placed, 41% of the recordings registered levels between 70–80 dBA and 0.2% between 80–90 dBA. Unsurprisingly, without the A-weighting, 28% of the recordings registered levels between 80-90 dBZ. No recordings registered levels below 30 dBA nor below 50 dBZ.

Table 7. Summary of Recording Session 1. A-and Z-weighted sound pressure levels and percentage values of the total number (N=596) of 10-minute recordings.

(Session 1, N=596)	***A-weighted (dBA)***		***No weighting (dBZ)***	
SPL	**Blue (%)**	**Red (%)**	**Blue (%)**	**Red (%)**
30-40		4.3		
40-50	**59.2**	31.6		
50-60	31.5	15.0	5.9	21.3
60-70	8.6	7.6	**58.1**	28.3
70-80	0.5	41.3	22.5	21.5
80-90	0.2	0.2	13.3	28.7
90-100			0.2	0.2

The A-weighted values provided above are already above and beyond the information normally provided to the medical practitioner, when worker noise exposure is questioned. Z-weighted values are not usually provided, nor requested. From this type of A-weighted data, the legislated permissible exposure levels (see Table 1) can be extrapolated. The time over which the worker is exposed to a particular A-weighted SPL can also be surmised in order to calculate an 8-hour exposure. The percentage values of the recordings given in Table 7 could provide some insight into the time over which workers are actually exposed to a specific SPL. For example, '59% of the recordings registered levels between 40–50 dBA' could be interpreted as 'the worker was exposed to these levels 59% of the time.' However, given that the SAM Scribe system is also measuring overnight, and the Paint Factory has no night shift (with the exception of the security guard), this extrapolation may be greatly misleading. Finer analyses curtailed to specific times of day are possible for this and all other recording sessions, but that is beyond the scope of this report. The sole information on the frequency distribution is given by the A-weighted values, which are designed to evaluate human hearing and, therefore, emphasize the 800-7000-hertz range.

3.2 TEMPORAL VARIATION OF A- AND Z-WEIGHTED SOUND PRESSURE LEVELS

With the type of data captured with the SAM Scribe system, it is possible to construct Time-of-Day Plots. Figure 7 shows an example of a Time-of-Day Plot, applied to all four Recording Sessions, analyzing the temporal variation of A-weighted and Z-weighted SPLs.

Each column is a 24-hour period, composed of 144 10-minute slots. Day (07:00-19:00), evening (19:00-23:00) and night (23:00-07:00) hours are indicated along the Y-axis. The corresponding day of the month of each 24-hour period is given in the X-axis. Each SPL indicated in each 10-minute slot (color scale on the right) corresponds to a 10-minute SAM Scribe recording. With this type of visualization, the time over which each worker is exposed to each SPL range is easily viewed. The color scale indicated on the right shows SPLs expressed in either dBA (Fig. 7, A-B) or dBZ (Fig. 7, C-D).

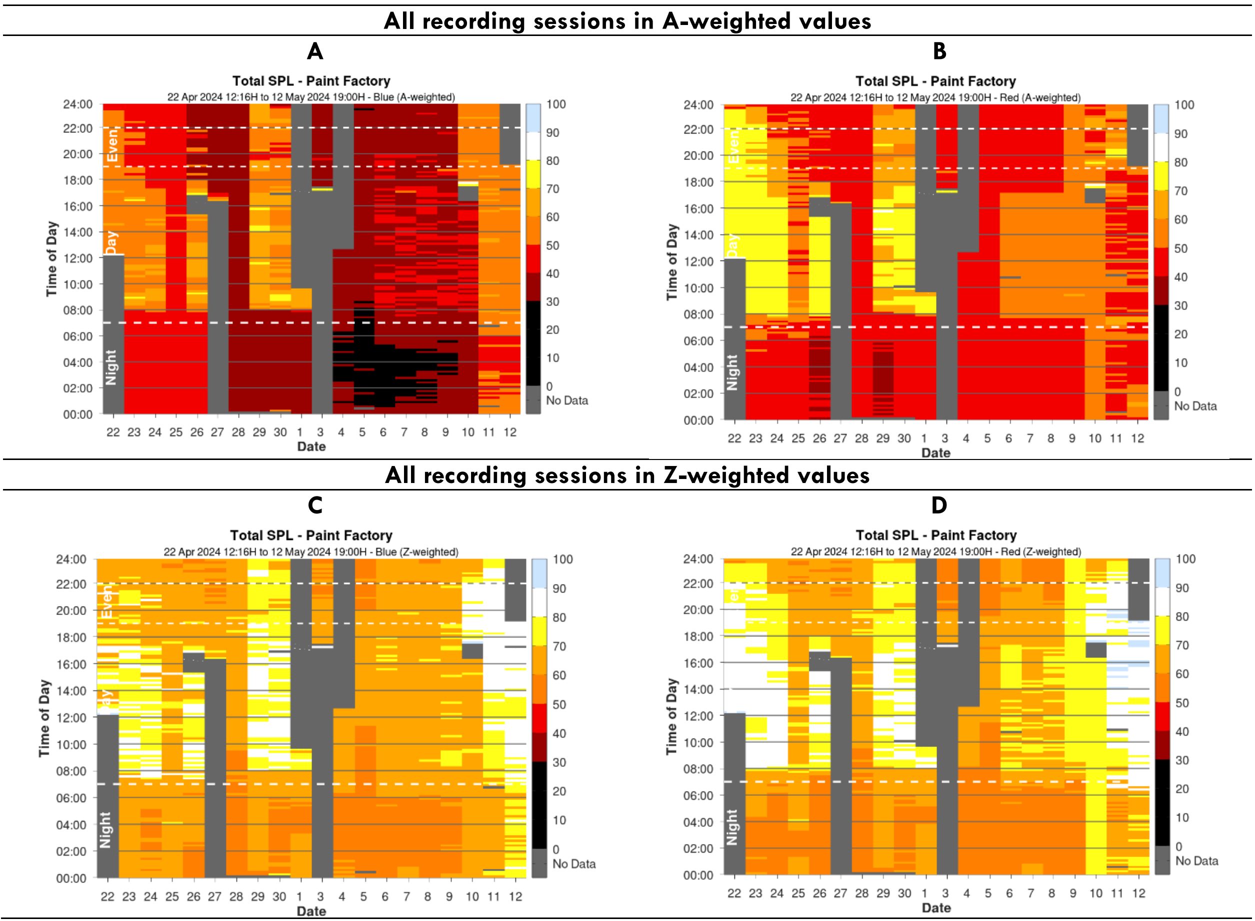

Figure 7. Time-of-Day plots, where each column represents 24-hours (144 10-minute slots). The average SPL value for each 10-minute slot is given by the color-coded scale, in dBA (A and B) and dBZ (C and D). Each recording session is indicated by the dates over which it was conducted—*Session 1*: 22–26 Apr; *Session 2:* 26 Apr–01May; *Session 3:* 03–10 May; and *Session 4:* 10–12 May.

This type of visualization of the acoustic environment provides, simultaneously, the A- or Z-weighted SPLs at which workers are exposed and the time over which such exposures occur. Not only is this very useful data for the informed clinician but it is also a powerful tool to locate the noise source. With two microphones, the relative position of the noise source can be identified. By analyzing its temporal behavior, it is possible to pinpoint the exact machine producing that particular acoustic output.

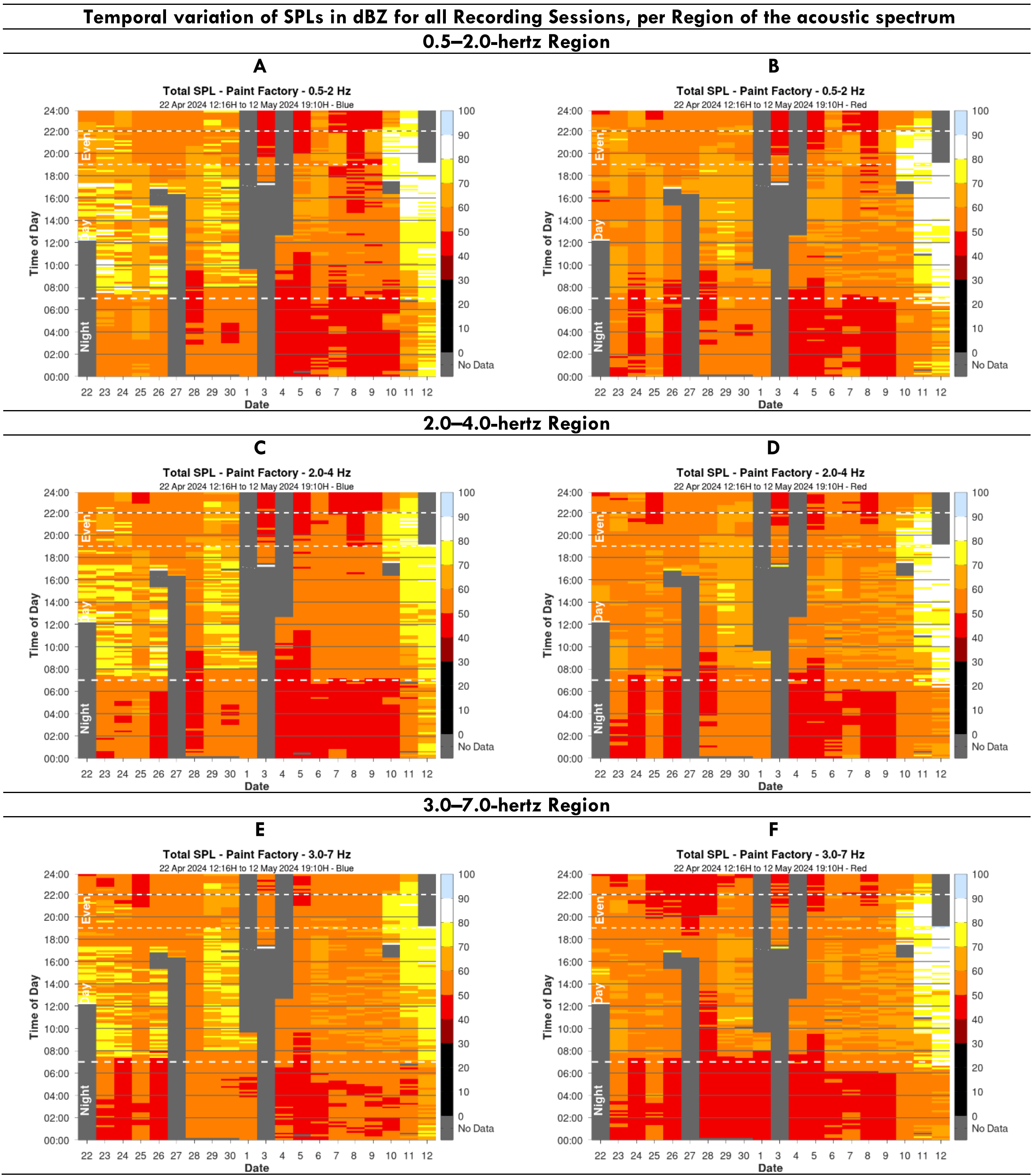

Figure 8. Time-of-Day plots, where each column represents 24-hours (144 10-minute slots). The average SPL value for each 10-minute slot is given by the color-coded scale, in dBZ. Each recording session is indicated by the dates over which it was conducted—*Session 1*: 22–26 Apr; *Session 2*: 26 Apr–01 May; *Session 3*: 03–10 May; and *Session 4*: 10–12 May. (A) and (B) show the SPL variation within the 0.5–2.0-hertz frequency range. (C) and (D) show the SPL variation within the 2.0–4.0-hertz frequency range. (E) and (F) show the SPL variation within the 3.0–7.0-hertz frequency range. All SPLs are expressed in dBZ.

3.3 FREQUENCY VARIATION OF Z-WEIGHTED SOUND PRESSURE LEVELS

The justification for the acoustic segmentation used in this report was described in section 1.5 and Table 6. The same Time-of-Day plots are now constructed only with SPLs in dBZ (unweighted values) and only within specific segments (or Regions) of the acoustic spectrum. Figure 8 shows the results for the first three segmented Regions (Table 6): 0.5–2.0 Hz, 2.0–4.0 Hz, and 3.0—7.0 Hz. At a glance, the clinician can now ascertain how long the worker is exposed to a specific SPL and within a narrow frequency range.

As an example, it is interesting to analyze what occurs in Recording Session 4 (10–12 May), inside and outside the Security Office (see Figure 6, Figure 8 and Table 1), during the 07:00–19:00 work shift. Within the 0.5–2.0-hertz range (Figure 8B), the time over which the worker inside the Security Office spends at SPLs between 80–90 dBZ is significantly longer than the time spent at these SPLs and frequencies when outside of the Security Office (Fig. 8A), where levels are mostly within the 70—80 dBZ. The same occurs within the subsequent spectral Regions:

the worker inside the Security Office is exposed to higher levels for longer periods of time, at all frequencies below 7 Hz.

At a glance, it can be easily verified that within the three spectral Regions presented herein, and among all 4 recording sessions (8 distinct workstations), the interior of the security office is the workplace where workers have the highest exposure to acoustic phenomena (>80 dBZ) for longer periods of time (hours). This contrasts with the data obtained with A-weighting, as shown in Figure 7 A-B. Outside the Security Office, SPLs are between 60–70 dBA, while levels inside the Security Office are mostly below 50 dBA, with occasional short-lived time intervals at levels between 50–60 dBA—both well within the permissible exposure levels given in Table 1.

4. Discussion

4.1 NOISE-INDUCED NON-AUDITORY PATHOLOGY

4.1.1 Immediate effects

The notion that acoustic phenomena have to be perceived via the auditory system, otherwise there is no influence on health is far outdated. In a 1978 paper, almost 50 years ago, the French Laboratory of Acoustic Physiology (Jouy-en-Josas) demonstrated that *genetically deaf mice* exhibited decreased performance when exposed to infrasound, but not when exposed to audible noise.[27] Normal hearing mice had decreased performance with both exposures. This demonstrates that the effects of infrasound on mammalian creatures can be independent of the auditory apparatus.

More recently, in 2017, a multi-group research team based in Germany studied the effects of a 12-hertz pure-tone on the brain, using functional MRI.[28] Tones administered through the ear were shown to also be processed by regions of the brain associated with emotional and autonomic control, and not solely via the known auditory pathways. In 2021, another group based in Germany showed that direct application of pure-tone infrasonic stimulus (16 Hz), at 110 or 120 dBZ, caused the heart tissue to reduce contraction strength by 11% and 18%, respectively.[29] These types of studies are mostly being conducted within the scope of residential noise exposures associated with wind power plants.

Over the past three decades, studies investigating infrasonic exposures within the context of occupational settings have mainly been conducted by Chinese scientists, presumably due to the immense activity of their Space Program. The series of studies conducted by these Chinese scientists exposed animal models to well-defined, pure-tone infrasonic doses, for 2 hours/day, over several weeks. With this type of exposure protocol, fine physiological pathways were then analyzed.

For example, the expression of NMDAR1 (N-methyl-D-aspartate) and changes in intracellular calcium concentrations in rat hippocampal nerve cells were evaluated after an acoustic stimulus of 8Hz/90 dB or 8Hz/130 dB, applied for 2 hours/day, for several weeks. Intercellular calcium concentrations were greatly increased, leading to a marked inhibition in the expression of NMDAR1, hindering learning and memory.[30] In another ground-breaking study, mechano-sensitive channels (TRPV4) expressed by rat glial cells were studied after exposure for 2 hours/day to 8 or 16 Hz, at 90, 100 or 130 dB, over several weeks. Results showed that the TRPV4 channel was abundantly expressed and could account for the neuronal cell death as well as animal learning and memory deficits.[31] More recently, 2 hour/day exposures to 16 Hz at 130 dB, over 14 days, revealed that by downregulating hippocampal connexin 43 hemichannels (usually activated under pathological conditions), impaired learning and memory were significantly alleviated.[32] To these authors' knowledge, no subsequent or ongoing infrasound studies on humans have been published in the English language.

4.1.2 Long-term effects

Long-term effects of occupational noise exposure on extra-auditory pathology have also been studied for at least 5 decades. In a 1976 paper, published by the US Occupational Safety and Health Administration (OSHA), 400 boiler-plant workers were evaluated before, and two years after, the implementation of the OSHA-guided hearing protection program.[33] The noise environment of these workers was simply characterized as 95 dBA or higher, with no information on frequency content. Job injuries, diagnosed disorders, symptomatic complaints, discrete absences and total absent days were registered. The authors eloquently concluded: "These general findings, with the exception of symptomatic complaints, uphold the hypothesis that there would be fewer reported extra-auditory problems for workers in high noise jobs subsequent to the establishment of a hearing conservation program."[33] Table 8 shows the nature and type of the symptomatic complaints registered among these boiler-plant workers.

Table 8. Symptomatic complaints reported by boiler-plant workers after the implementation of hearing conservation program.[33]

Organ system	Symptomatic Complaint
Allergenic & Dermatological	Skin itching, skin burning
Respiratory	Coughing, congestion in head and chest, shortness of breath, hoarseness
Neurological	Headaches, dizziness, numbness
Digestive	Stomach cramps, nausea, diarrhea, heartburn
Urological	Irregular urination, pain in bladder area, blood in urine
Muscular & Skeletal	Backaches and neckaches, soreness in muscles, cramps

Almost three decades ago, in 1999, a group of 140 aeronautical workers were selected from an initial group of 306 workers, and studied as to the development of extra-auditory signs and symptoms per years of occupational activity.[34] Exclusion criteria included history of diabetes, streptococcal infections, alcoholism, and neuroleptic drugs. Table 9 lists the symptoms (reported by workers) and signs (observed by the physician) when present in 50% of the population (i.e., in 70 workers), and per years of professional activity. Data was mostly obtained from workers' medical files and physician notes. Workers' noise environment was characterized as "large amplitude low frequency noise," <500 Hz and ≥90 dBA.

Table 9. Clinical stages of the noise-induced pathology observed in aeronautical technicians, per years of occupational activity (adapted from [34])

Clinical Stage	Signs & Symptoms
Mild *(1-4 yrs)*	Slight mood swings, indigestion & heartburn, repeated mouth & throat infections, bronchitis
Moderate *(4-10 yrs)*	Chest pain, back pain, fatigue, fungal & viral skin infections, allergies, blood in urine, inflammation of the stomach lining
Severe *(>10 yrs)*	Psychiatric disturbances, headaches, hemorrhages of nasal and digestive mucosa, duodenal ulcers, spastic colitis, varicose veins & hemorrhoids, decreased vision, severe joint pain, severe muscular pain, neurological disturbances

In 2001, the vascular changes in the palpebral and bulbar conjunctiva and in the retina were investigated among 214 reinforced-concrete factory-workers.[35] Noise exposure was characterized as tonal at 8 and 16 Hz, 96–100 dB, simultaneous with non-tonal noise described as 20–500 Hz at 91–93 dBA. The results of this study are given in Table 10, per occupational exposure time.

Table 10. Percentage of vascular abnormalities in palpebral, bulbar and retinal arteries and veins, per years of occupational activity (adapted from [35]).

Occupational Exposure Time	1-2 yrs	3-10 yrs	11-20 yrs	20-30 yrs
Number of workers	*21*	*84*	*36*	*19*
Palpebral & bulbar arteries (%)				
Enlarged	0	82	8	0
Narrow	0	17	91	100
Twisted	0	80	100	100
Retinal arteries (%)				
Enlarged	0	0	0	0
Narrow	0	91	100	100
Twisted	0	90	100	100
Retinal veins (%)				
Enlarged	0	87	11	0
Narrow	0	13	88	100
Twisted	0	75	97	100

When long-term effects are investigated under a proper study design, results may appear stunning, as those shown here. Despite the long-standing knowledge of these effects, noise-exposed workers are still only evaluated as to their hearing acuity and, possibly, their level of noise annoyance.

4.2 G-WEIGHTING, ISO STANDARDS AND THE WORLD HEALTH ORGANIZATION–PROFOUNDLY CONTRADICTORY POSITIONS

Over the decades, some efforts have been made to 'deal with' the infrasound problem. In 1995, ISO published an international standard (ISO 7196:1995(E)) dedicated to *Frequency-weighting characteristic for infrasound measurements*.[36] In its Introduction, the following is stated:

> *The method described in this International Standard corresponds to the direct perception of infrasound. At present, this is the only human response for which there is an ample research base. Some literature on annoyance from infrasound suggest that annoyance may be loosely related to the direct perception. On that precondition, levels measured according to this International Standard would reflect that annoyance as well as the direct perception.*[36]

For the uninitiated, the above paragraph may be confusing. It suggests that the "direct perception of *infrasound*" is "loosely related" to subjective levels of annoyance—the higher the levels of infrasound, the higher the levels of annoyance. Thus, ISO justifies the application of G-weighting on acoustic measurements.

The above paragraph may be interpreted to be in blatant contradiction with the position taken by the authors of this report. In fact, it is in contradiction with WHO definitions:

> *An adverse effect of noise is defined as a change in the morphology and physiology of an organism that results in impairment of functional capacity, or an impairment of capacity to compensate for additional stress, or increases the susceptibility of an organism to the harmful effects of other environmental influences.*[37]

Strictly speaking from the standpoint of Medical Sciences, *annoyance* is not considered a medical endpoint. In the 2017 edition of Mosby's Medical Dictionary and in the 2018 edition of the Medical Dictionary published by the British Medical Association, there are zero instances of the word annoyance. The 2020 edition of the Oxford Medical Dictionary and in the 2020 edition of Dorland's Illustrated Medical Dictionary, both contain one single instance of this word:

> *Glare: the undesirable effects of scattered stray light on the retina, causing reduced contrast and visual performance as well as **annoyance** and discomfort.*[38]
>
> *Irritable: 1. Capable of reacting to a stimulus. 2. Abnormally sensitive to a stimulus. 3. Prone to excessive anger, **annoyance**, or impatience.*[39]

To date, the most comprehensive definition for *noise annoyance* seems to be the one provided in 2000 by the European Commission Noise Team:

> *Annoyance is the scientific expression for the non-specific disturbance by noise, as reported in a structured field survey. Nearly every person that reports to be annoyed by noise in and around its home will also experience one or more of the following specific effects: Reduced enjoyment of balcony or garden; When inside the home with windows open: interference with sleep, communication, reading, watching television, listening to music and radio; Closing of bedroom windows in order to avoid sleep disturbance. Some of the persons that are annoyed by noise also experience one or more of the following effects: Sleep disturbance when windows and doors are closed; Interference with communication and other indoor activities when windows and doors are closed; Mental health effects; Noise-induced hearing impairment; Hypertension; Ischemic heart disease.*[40]

As described above, therefore, annoyance is an excellent psychoacoustic parameter, by which worthy sociometric studies can be conducted. It is not, however, a clinical 'Response' within the context of *Dose-Response* relationships, as required by Medical Sciences. In fact, a search of the word *annoyance* in ICD-10 and ICD-11 produced zero results.

To these authors' knowledge, the ISO 7196:1995(E) is only applied to environmental noise exposures and not to occupational noise settings (yet). Nevertheless, it would seem interesting and appropriate to (pre-emptively) present the Paint Factory data with the application of G-weighting—see Figure 9—which yields SPLs in the dBG metric. Table 4 recalls the placement of each microphone in each Recording Session.

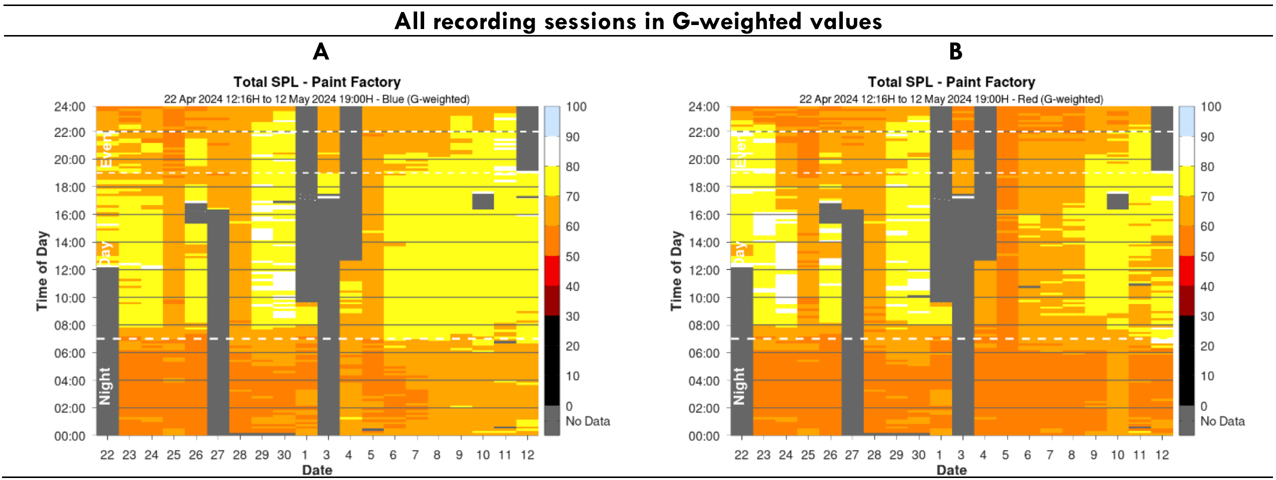

Figure 9. Time-of-Day plots, where each column represents 24-hours (144 10-minute slots). The average SPL value for each 10-minute slot is given by the color-coded scale, in dBG (A and B). Each recording session is indicated by the dates over which it was conducted—*Session 1*: 22–26 Apr; *Session 2*: 26 Apr–01 May; *Session 3*: 03–10 May; and *Session 4*: 10–12 May.

The highest G-weighted SPLs (80–90 dBG) that exist over the longest periods of time occur in the Filling Unit Office (Blue mic, Recording Session 2, Fig. 9A) and in the Manufacturing Area (Red mic, Recording Session 1, Fig. 9B). There is a significant difference in G-weighted SPLs in Recording Session 3, where the Quality Office (Blue mic, Fig. 9A) registers practically continuous levels between 70–80 dBG, while the R&D Lab (Red mic, Fig.

9B) registers levels between 60–70 dBG with sporadic and short-lived (10 to 30 minutes) events reaching 70–80 dBG.

Of these 8 workstations, the R&D Lab appears to be the one with lowest G-weighted SPLs over time. In theory, therefore, all conditions being similar, it would be the R&D Lab workers that would exhibit the lowest levels of noise annoyance. The highest levels of annoyance would be expected amongst workers of the Manufacturing Area and the Filling Unit Office, although other workstations may also be problematic. As a physical agent of disease, 'noise' has a cumulative effect on the biological organism, similar to radiation and vibration exposures. Therefore, verification of the predicted levels of annoyance (as suggested by Fig. 9) among these Paint Factory workers should only be conducted if the study and control populations of workers are stratified into years of professional activity (and not age), as shown in Tables 9 and 10. Prior noise-exposure histories of all workers must also be ascertained. Without these two study-design features, statistically invalid data will (regrettably) be the probable outcome.

4.3 INFRASOUND LEGISLATION IN A NON-EU-MEMBER STATE

In the Russian Federation, infrasound is considered a harmful and dangerous factor.[41] There are very specific, extensive and compulsory neurological and cardiovascular examinations afforded to workers exposed to infrasound.[42-44] Specific infrasound legislation has been in place since the 1980's [45] with current permissible exposure values, for both occupational and residential areas, given in Figure 10.

Clearly, a different and, perhaps, more scientifically based approach is taken by the health authorities of the Russian Federation when it comes to infrasonic exposures of their workers, and of their population at large.

Premise	Sound pressure levels, dB, in octaval bands of averaged geometric frequencies, Hz				General sound pressure level dB "Lin"
	2	4	8	16	
Different jobs inside industrial premises and production areas:					
- Different physical intensity jobs	100	95	90	85	100
- Different intellectual emotional tension jobs	95	90	85	80	95
Populated area	90	85	80	75	90
Living and public premises	75	70	65	60	75

Figure 10. Permissible exposure levels for infrasound (reproduced from[45]). The infrasonic ranges are segmented into octaves and SPLs are given in dBZ (also known as dB Lin).

4.4 SCIENTIFIC OBSTACLES

In general, acousticians are not medically trained, and medical practitioners are not proficient in acoustics. The majority of acousticians are told that annoyance is a *bona fide* health endpoint, and its correlation to infrasonic exposures is supported by ISO 7196:1995(E), through which acousticians are given precise methodologies on how to 'evaluate infrasound.' Medical school curricula, on the other hand, rarely include noise exposures, even within the scope of Public Health.[46] Auditory acuity becomes the purview of otorhinolaryngologists (or ENTs–ear, nose and throat specialists) and for these professionals, only the A-weighted value is important as it is directly related to hearing loss. With the possible exception of Military Medicine, very rarely do medical practitioners seek to understand the effects of infrasound and lower frequency noise on the workers under their care.

Basic science research investigating the effects of noise on the various objects of study should not be compelled to characterize their noise environments as per legislated methodologies. And yet, the vast majority of noise-and-health related studies conducted today, exclusively use A-weighting to characterize their noise environments. If they are focusing on the hearing apparatus alone, then this position could be justified. However, if, for example, the development of cardiovascular disease with noise exposure is the focus, then a mere A-weighted (or G-weighted or Z-weighted) SPL value is quite insufficient—the frequency content of the environment is a *sine qua non* variable that must be accounted for. Perhaps more worrisome are the studies that do not consider noise exposures as confounding factors. For example, those investigating the effects of air pollution or life-style habits on health, among many others. Even animal studies, usually conducted within laboratories, do not account for the (often variable) noise environment, and yet, it is an inextricable part of their study animals' environment. Perpetuating this *status quo* helps no one, save that changing the established (and fossilized) practices would require significant financial support to be remedied.

New lines of research among possible clinical Responses to infrasonic and low frequency noise exposures are emerging, for example in the studies by Alimohammadi *et al.*[47] and Dastan *et al.*[48]. But without the proper characterization and quantification of the *Dose*, no data for the *Dose-Response* relationship can be reliably gathered.

4.5 FINAL COMMENTARY

The flexibility of analyses that can be achieved with this type of acoustic recording announces a new era of scientific avenues to explore. No longer are acoustic environments restricted to being characterized by the crude, aggregated, metrics inherited from the past century. The segmentation of the acoustic spectrum presented herein is merely an example. Practically any narrow frequency band can now be studied, simultaneously accounting for the variables of time and SPL.

For the past 20 years, these technological advances have already been applied to acoustics studies in areas other than within the Medical Sciences. For example, infrasound has been used to study earthquakes[49] and tornado storms;[50] it is also being used for early-warning detection of avalanches,[51] and to monitor volcanos.[52] Could not 21st-century digital technology be brought into the realm of Medical Sciences, in particular, to the fields that study the 'effects of noise on health'?

5. Conclusions

The way in which *noise* is evaluated is light-years behind the times. Based on pre-digital technologies, current noise evaluation methodologies are outdated and of very low temporal and spectral resolutions. Quantifying the *noise dose* with these legally binding, but antiquated, methodologies mislead clinicians as to the real physical exposure of their worker-patients. Clinicians need to be reeducated regarding the description of the acoustic environments of the workers under their care. They must (justifiably) demand more information on the noise dose and must cease to rely solely upon A-weighted values.

Conflict of interests

The authors have no conflict of interest to declare—No author has any financial interest in the SAM Scribe System.

Funding statement

The SAM Scribe System used in this study is on loan to author PPS by the International Acoustics Research Organization.

Acknowledgements

The authors thank the Administrators of the Paint Factory who so kindly allowed acoustic recordings to be conducted. The authors also thank Dr. Bruce Rapley and Dr. Philip Dickinson for their long-standing support and invaluable insights.

References

1. European Parliament and Council Directive, EU Directive 2003/10/CE, 6 February. On the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0010
2. Portuguese Ministry of Labor and Social Solidarity. Decree-Law No. 182/2006, 6 September. Diário da República n.° 172/2006, Série I 2006-09-06, pp. 6584 – 6593. https://dre.pt/dre/detalhe/decreto-lei/182-2006-539986.
3. Fletcher H, Munson WA. Loudness, its definition, measurement and calculation. *JASA*. 1933;5: 82-108. https://www.sfu.ca/sonic-studio-webdav/AudioMedia/Readings/Misc.%20Readings/Loudness%2C%20Its%20Definition%2C%20Measurement%20and%20Calculation%20.pdf
4. ISO-International Standards Organization. ISO 226:2023-3–Acoustics: Normal equal-loudness-level contours. https://www.iso.org/standard/83117.html
5. Pereira-Sousa P, Bakker HCB, Alves-Pereira M. Dose-Response relationship in occupational noise exposures: The distorted quantification of dose that misinforms the medical community. *Proc SHO2025* (International Symposium on Occupational Safety and Hygiene). Porto, Portugal 14 April 2025: 025-32. https://books.fe.up.pt/index.php/feup/catalog/book/978-989-54863-7-3/chapter/347
6. Hirsch J, Nicola G, McGinty G, Liu RW, Barr RM *et al.* ICD-10: History and Context. *AJNR*. 2016;37:596-599. https://www.ajnr.org/content/37/4/596x
7. WHO—World Health Organization. International Classification of Diseases (ICD-10). https://icd.who.int/browse10/2019/en#/W20-W49
8. WHO—World Health Organization. International Classification of Diseases (ICD-11). https://icd.who.int/browse/2026-01/mms/en#850137482
9. WHO—World Health Organization. International Classification of Diseases (ICD-11). Keyword "vertigo." https://icd.who.int/ct/icd11_mms/en/2026-01
10. Project Poorboy. Annual Progress Report. *Defense Technical Information Center*. Report No. 4139.11-R-1; 1968. https://archive.org/details/DTIC_AD0830775/page/n3/mode/2up
11. Shoenberger RW. Human response to whole body vibration. *Percep Mot Skill*. 1972;34:127-60. https://pubmed.ncbi.nlm.nih.gov/4551872/
12. Dieckmann D. A study of the influence of vibration on man. *Ergonomics*. 1958;1(4):347-355. https://www.semanticscholar.org/paper/A-STUDY-OF-THE-INFLUENCE-OF-VIBRATION-ON-MAN-Dieckmann/82fb84a29b20126049eee426481cdfcb3fed9c17
13. Coermann RR. The mechanical impedance of the human body in sitting and standing position at low frequencies. *Human Factors*. 1962;Oct:227- 253. https://pubmed.ncbi.nlm.nih.gov/14021944/
14. Edwards RG, Lange KO. A mechanical impedance investigation of human response to vibration. *Defense Technical Information Center*. Aerospace Medical Research Laboratories Technical Report No. 64-91; 1964. https://archive.org/details/DTIC_AD0609006/page/11/mode/2up
15. Guignard JC. The physical response of seated men to low-frequency vertical vibration. Air Ministry Flying Personnel Research Committee. FPRC Report No. 1062; 1959. Cited in: Kinney JAS, Luria SM, Markowitz H. The effect of vibration on visual acuity with electro-optical aids to night vision. *Human Factors*. 1971;13(4):369-78. https://pubmed.ncbi.nlm.nih.gov/5118775/
16. Pei Z, Sang H, Li R, Xiao P, He J, Zhuang Z, *et al.* Infrasound-induced hemodynamics, ultrastructure, and molecular changes in the rat myocardium. *Environ Toxicol*. 2007;22:169-175. https://pubmed.ncbi.nlm.nih.gov/17366570/
17. Antunes E, Oliveira P, Borrecho G, Oliveira MJR, Brito J, Águas A, *et al.* Myocardial fibrosis in rats exposed to low frequency noise. *Acta Cardiol*. 2013;68:241-245. https://pubmed.ncbi.nlm.nih.gov/23882868/
18. Zhang MY, Chen C, Xie XJ, Xu SL, Guo GZ, Wang J. Damage to hippocampus of rats after being exposed to infrasound. *Biomed Environ Sci*. 2016;29(6):435-42. https://pubmed.ncbi.nlm.nih.gov/27470104/
19. Alexeev SV, Glinchikov VV, Usenko VR. Infrasound induced myocardial ischemia in rats. *Gig Truda Prof Zabol*. 1983;8:34-38. [Article in Russian] https://pubmed.ncbi.nlm.nih.gov/6629078/
20. Bakker HCC, Alves-Pereira M, Summers R. A citizen science initiative: Acoustic Characterization of Human Environments. Paper presented at: International Conference on the Biological Effects of Noise (ICBEN 2017). 18-22 June 2017; Zurich, Switzerland. No. 3653, 12 pages. https://www.icben.org/2017/ICBEN%202017%20Papers/SubjectArea10_Bakker_1015_3653.pdf.
21. Bakker HCC, Rapley BI, Summers SR, Alves-Pereira M, Dickinson PJ. An affordable recording instrument for the Acoustical Characterisation of Human Environments. Paper presented at: International Conference on the Biological Effects of Noise (ICBEN 2017). 18-22 June 2017; Zurich, Switzerland. No. 3654, 12 pages. https://www.icben.org/2017/ICBEN%202017%20Papers/SubjectArea05_Bakker_P40_3654.pdf
22. Primomic. Electeret condenser microfone EM246ASS'Y—Technical Data. Primo Co. Ltd, Tokyo, Japan, 2016. https://primomic.com/pdf/EM246.pdf
23. Norwegian Center for Maritime and Diving Medicine. E7. Vibration. Textbook on Maritime Health; 2021. https://textbook.maritimemedicine.com/
24. Gora G, Iwaniec M, Kulinowski P, Gac K. Vibration impact on people transported by mining belt conveyors. *Vibrations in Physical Systems*. 2020;31:2020109. https://vibsys.put.poznan.pl/_journal/2020-31-1/articles/vibsys_2020109.pdf

25. Ashe WF. Physiological and pathological effects of mechanical vibration on animals and man. *Defense Technical Information Center*. Ohio State University, Report No. 862-4; 1961. https://archive.org/details/DTIC_AD0265931/page/n1/mode/2up
26. FAO—Food and Agriculture Organization of the United Nations. Introduction to ergonomics in forestry in developing countries. FAO Forestry Paper No. 100. 1992. https://www.fao.org/4/ap419e/ap419e00.pdf
27. Busnel RG, Lehmann AG. Infrasound and sound: Differentiation of their psychophysiological effects through use of genetically deaf animals. *JASA*. 1978;63:974-77. https://pubmed.ncbi.nlm.nih.gov/670562/
28. Weichenberger M, Bauer M, Kuhler R, Hensel J, Forlim CG, Ihlenfeld A, *et al*. Altered cortical and subcortical connectivity due to infrasound administered near the hearing threshold: Evidence from fMRI. *PLoS ONE*. 2017;12(4):e0174420. https://pubmed.ncbi.nlm.nih.gov/28403175/
29. Chaban R, Ghazy A, Georgiade E, Stumpt N, Vahl CF. Negative effect of high-level infrasound on human myocardial contractility: In-vitro controlled experiment. *Noise & Health*. 2021;23:57-66. https://pubmed.ncbi.nlm.nih.gov/34213448/
30. Liu ZH, Chen JZ, Ye L, Liu J, Qiu JY, Xu J. *et al*. Effects of infrasound at 8 Hz 90 dB and 130 dB on NMDAR1 expression and changes in intracellular calcium ion concentration in the hippocampus of rats. *Mol Med Rep*. 2010;3:917-921. https://pubmed.ncbi.nlm.nih.gov/21472333/
31. Shi M, Du F, Liu Y, Li L, Cai J, Zhang GF, *et al*. Glial cell-expressed mechanosensitive channel TRPV4 mediates infrasound-induced neuronal impairment. *Acta Neuropathol*. 2013;126:725-39. https://pubmed.ncbi.nlm.nih.gov/24002225/
32. Zhang W, Yin J, Gao BY, Lu X, Duan YJ, *et al*. Inhibition of astroglial hemichannels ameliorates infrasonic noise induced short-term learning and memory impairment. *Behav Brain Funct*. 2023;19:23. https://pubmed.ncbi.nlm.nih.gov/38110991/
33. Cohen A. The influence of a company hearing conservation program on extra-auditory problems in workers. *J Saf Res*. 1976;8:146-62. https://scispace.com/papers/the-influence-of-a-company-hearing-conservation-program-on-4x44gaqygr
34. Castelo Branco NAA. The clinical stages of vibroacoustic disease. *Aviat Sp Environ Med*. 1999;70 (3, Pt 2): A32-39. https://pubmed.ncbi.nlm.nih.gov/10189154/
35. Kosacheva TI, Svidovyi VI, Alekseev VN, Kovalenko VI. Influence of noise and infrasound on the vision organs. *Med Tr Prom Ekol*. 2001;(6):34-38. [Article in Russian] https://pubmed.ncbi.nlm.nih.gov/11521298/
36. ISO—International Standards Organization. ISO 7196:1995(E). Acoustics. Frequency-weighting characteristic for infrasound measurements. https://www.iso.org/standard/13813.html
37. WHO—World Health Organization. Guidelines for community noise. Stockholm, Sweden: Stockholm University & Karolinska Institute; 1999. https://www.who.int/publications/i/item/a68672
38. Martin EA, Law J. (Eds). Concise Colour Medical Dictionary. 7th Ed. Oxford, UK: Oxford University Press; 2020.
39. Dorland's Illustrated Medical Dictionary. 33rd Ed. Philadelphia: Elsevier Saunders; 2020
40. European Commission. (2000) The Noise Policy of the European Union—Year 2. Towards improving the urban environment and contributing to global sustainability. European Commission Noise Team: Luxembourg. https://www.europeansources.info/record/the-noise-policy-of-the-european-union-year-2-1999-2000-towards-improving-the-urban-environment-and-contributing-to-global-sustainability/
41. Russian Federation Federal Law. No. 426-FZ. On a special assessment of working conditions. 2013. https://www.russiangost.com/p-370713-federal-law-426-fz.aspx
42. Russian Federation Norm No. GN 2274-80. Hygienic norms of infrasound in the workplace. 2013. https://www.russiangost.com/p-286222-gn-2274-80.aspx
43. Russian Federation Order No. 29n. On the approval of the Procedure for conducting mandatory preliminary and periodic medical examinations of employees, provided for in part four of Article 213 of the Labor Code of the Russian Federation, a list of medical contraindications to work with harmful and (or) hazardous production factors, as well as work in which mandatory preliminary and periodic medical examinations. 2021. https://www.russiangost.com/p-382607-order-29n.aspx
44. Russian Federation Order No. 75n. On approval of the procedure for mandatory medical examinations before the work shift, medical examinations during the work shift (if necessary) and medical examinations after the work shift (if necessary) of workers engaged in underground work with hazardous and (or) harmful working conditions in coal (oil shale) mining (processing), including the use of technical means and medical devices that provide automated remote transmission of information about the health of workers and remote monitoring of the state of health. 2022. https://www.russiangost.com/p-430834-order-75n.aspx
45. Stepanov V. Biological effects of low frequency acoustic oscillations and their hygienic regulation. State Research Center of Russia, Moscow, 2001. https://archive.org/details/DTIC_ADA423963
46. Aletta F. Noise pollution and public health curricula: a missing link in environmental health preparedness. *Academia Global & Public Health*. 2025;1(1). https://doi.org/10.20935/AcadPHealth8070
47. Alimohammadi I, Rafieepour A, Ashtarinezhas A, Hosseni AF, Tabatabaei SH, Jafari H, *et al*. Occupational noise annoyance and sensitivity as potential contributors to oxidative stress in metal industry workers. *Sci Rep*. 2025;15:30280. https://pubmed.ncbi.nlm.nih.gov/40825830/

48. Dastan M, Parente-Ribeiro ED, Bellut-Staeck U, Zhou J, Lehmann C. Infrasound and human health: mechanisms, effects and applications. Applied Sciences. 2026;15:1553. https://www.mdpi.com/2076-3417/16/3/1553
49. Mutschlecner JP, Whitaker RW. Infrasound from earthquakes. *J Geophys Res*. 2005;110(D1): D01108. https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2004JD005067
50. Waxler R, Frazier WG, Talmadge CL, Liang B, Hetzer C, Buchanan H, et al. Analysis of infrasound array data from tornadic storms in southeastern United States. JASA. 2024;156:1903-19. https://pubmed.ncbi.nlm.nih.gov/39302133/
51. Marchetti E, Ripepe M, Ulivieri G, Kogelnig A. Infrasound array criteria for automatic detection and front velocity estimation of snow avalanches: towards a real-time early-warning system. *NHESS*. 2015;15 (11):2545-55. https://nhess.copernicus.org/articles/15/2545/2015/
52. Marchetti E, Ripepe M, Campus P, Le Pichon A, Vergoz J, Lacanna G, *et al*. Long-range infrasound monitoring of Etna volcano. *Sci Rep*. 2019;9(1):18015. https://pubmed.ncbi.nlm.nih.gov/31784608/

