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Infrasound and low frequency noise dose responses: Contributions

Mariana Alves-Pereira[a] and Nuno A. A. Castelo Branco[b]
ERISA-Universidade Lusófona, Lisbon, Portugal
Center for Human Performance, Alverca, Portugal

ABSTRACT

The acoustical spectrum is usually divided into two major segments: that which can be heard by the human ear, and that which cannot. Moreover, it is usually maintained that if acoustical phenomena do not hurt the ear, then they will have no other bodily effects. In the electromagnetic (E&M) spectrum, there is also a segment capable of being perceived by human senses: visible radiation (light). However, unlike the acoustical spectrum, the E&M spectrum is not crudely divided in what is visible to the human eye, and what is not, nor is it assumed that E&M phenomena only cause bodily damage when they are *seen*. This is why it is possible to establish dose-responses for many different types of radiation (visible or not). A similar stance regarding the acoustical spectrum is required if dose-responses to infrasound & low frequency noise (ILFN, <500 Hz) are genuinely desired. This report focuses on information gathered over the past 27 years of research into the biological effects of ILFN exposure, with the goal of contributing to the establishment of ILFN dose-responses. A more detailed segmentation of the acoustical spectrum is proposed in order to adequately characterize acoustical environments.

1 INTRODUCTION

To consider dose-responses to infrasound and low frequency noise (ILFN, <500 Hz)) in a meaningful way, one must begin by recognizing that acoustical events are wave phenomena. Hence, for ILFN to be quantified in a manner that is useful for dose-response issues, the physical nature of this agent must be fully taken into account.

Given everyone's acquaintance with electromagnetic (E&M) radiation, also a wave phenomenon, it is worthwhile to expand on how E&M radiation is viewed when it comes to dose-responses. The similarity between the acoustical and E&M spectra is important to understand how biological tissue can be affected differently by the different frequencies and amplitudes associated with wave phenomena.

Like acoustical phenomena, a portion of the E&M spectrum is perceived by human senses, and is called visible light. Sound, on the other hand, is the portion of the acoustical spectrum that is perceived by humans. When E&M radiation is discussed, it is essential to refer the frequency of the radiation in question, i.e., microwave, infrared, x-ray, etc. In fact, some small segments are even broken up into smaller portions, such as ultraviolet (UV) radiation, that can be UV-A, UV-B or UV-C. No such segmentation exists for the acoustical spectrum. See Table 1.

[a] Email address: m.alvespereira@gmail.com
[b] Email address: vibroacoustic.disease@gmail.com

Table 1: Comparison between the detailed frequency/wavelength bands of a small portion of the E&M spectrum versus the rudimentary division of the acoustical spectrum.´

			Frequency (Hz)	Wavelength (m)	Effects
ELECTROMAGNETIC PHENOMENA					
Small Portion of the E&M Spectrum	***Ultraviolet***		0.75-3.0 ($x10^{15}$)	100 – 400 ($x10^{-9}$)	
		UV-A	0.75 – 0.95 ($x10^{15}$)	315-400 ($x10^{-9}$)	Skin cancers
		UV-B	0.95 – 1.07 ($x10^{15}$)	280-315 ($x10^{-9}$)	Cataracts
		UV-C	1.07 – 3.0 ($x10^{15}$)	100-280 ($x10^{-9}$)	
	Visible		0.42-0.75 ($x10^{15}$)	400 – 700 ($x10^{-9}$)	Vision
ACOUSTICAL PHENOMENA					
Entire Acoustical Spectrum	***Infrasound***		0-20	0-17	Pericardial thickening
	Audible		20-20000	17 – 0.01	
		LFN	20-500	6.8 – 0.68	Thoracic cavity resonance
		Hearing	1000-8000	0.34 – 0.04	Hearing impairment / Deafness
	Ultrasound		> 20000	< 0.01	Lithrotripsy, Medical diagnostics

Science has tended to divide the acoustical spectrum in a rudimentary fashion: infrasound audible, and ultrasound. Infrasound and ultrasound are not audible to (most) humans. There is no further segmentation. The resolution of information that science has chosen to scrutinize within the E&M spectrum is vastly superior to the rough and fuzzy segmentation that has been applied to the acoustical spectrum. Metaphorically, it would be like comparing Michael Angelo's realism with Monet's impressionism. Dose-response relationships cannot be adequately studied if the information of the physical agent is fuzzy. Parameters that define the physical agent must be taken into account if an adequate evaluation of the biological response is, indeed, desired.

The amplitude parameter of acoustical phenomena is usually expressed in dB (decibel). Scientific studies often regard this parameter as sufficient to characterize an acoustical environment. While this may be true (under certain circumstances) if the object of the evaluation is hearing protection, when IFLN dose-responses are the issue, a dB-level parameter alone is entirely insufficient.

The goal of this report is to shed some light on the shift in concepts that is required if dose-responses to ILFN are to be seriously considered.

2 BIOLOGICAL RESPONSES TO ILFN

The pathology that develops as a consequence of excessive ILFN exposure is called vibroacoustic disease (VAD) (1,2). For the past 27 years, the authors have been part of a multi-disciplinary team of researchers who have studied the biological effects of ILFN exposure in human (3,4 for example) and animal models (5,6 for example), as well as the clinical manifestations of VAD in humans (1,2). Resonance frequencies of the different tissues and organs play a significant role in the biological response to ILFN, as would be expected of any vibratory phenomena interacting with a substance. Specific features of cellular, tissue and organ responses to ILFN exposure, such as mechanotransduction (for example) (7), are essential to understanding how to establish dose-responses to ILFN.

The following sections describe some of the data that are useful for ascertaining ILFN dose-responses. Some of the working hypotheses that have been developed and successfully corroborated are also listed.

2.1 Animal Studies

ILFN-exposed animal models (Wistar rats) have been employed by this team since 1992 (5,6,8,9). The following studies were conducted within the context of VAD-related research.

Tracheal epithelia were studied in 12 rats after 48 hours of continuous ILFN (10). Another 12, age-matched rodents were kept in silence, and were considered controls. After the 48-hour exposure ceased, 2 rodents were immediately sacrificed, and another two after 6, 12, 24, 48 hours, and 7 days post-exposure silence. Fragments of the tracheal epithelia were studied and compared through scanning electron microscopy imaging. The damaged epithelial landscapes observed right after exposure were similar to those observed 6 hours after exposure. Twelve hours after exposure, some degree of recovery was seen, but damage was still visibly present when compared to controls. Few differences were identified between the 24- and 48-hour groups - recovery of epithelial cellular populations was well underway. After 7 days in post-exposure silence, exposed and control specimens were undistinguishable.

> ***Working Hypothesis-1:*** *after a 48-hour period of continuous ILFN exposure, the minimum recovery time (in silence) is 12 hours, but optimal recovery times require longer post-exposure (in silence) time periods.*

Third generation Wistar rats born in an occupationally-simulated (8hrs/day, 5days/week, weekends in silence) ILFN-rich environment were observed to have teratogenic malformations (11). In animals gestated and born in this ILFN-rich environment, the post-birth progression of respiratory tract lesions was investigated in groups exposed to additional ILFN for: 145 hrs (Group A), 235 hrs (Group B), 2213 hrs (Group C), 2438 hrs (Group D), 4399 hrs (Group E), and 5304 hrs (Group F) (11). The first discernible images of cellular de-differentiation (cellular organization precursor of cancerous lesions) were identified in Group D. Fusion of actin-based microvilli (located on the apical surface of brush cells) became visible in Group C, and were a regular occurrence in Group F. The genotoxicity of ILFN has been confirmed through sister chromatid exchanges assays (12).

> ***Working Hypothesis-2:*** *ILFN is a genotoxic agent that promotes congenital malformations and pre-cancerous lesions in rodent respiratory epithelia.*

2.2 Human Studies

Echocardiography in ILFN-exposed individuals reveals thickened pericardia, without diastolic dysfunction and in the absence of an inflammatory process (13-15). This feature is the hallmark of VAD (16). In 1999, when echocardiograms were obtained from both airline pilots and cabin crewmembers, an astounding result became apparent: with the same time of professional activity (in years), flight attendants presented a slower rate of pericardial

thickening when compared to pilots (14). Theoretically, the cabin is "noisier" than the cockpit, and thus, one would have expected to see a faster rate of pericardial thickening in cabin crewmembers. But this was not the case. After a detailed acoustical analysis of the cockpit and cabin of 8 commonly used commercial airline aircraft, it was demonstrated that the levels of infrasound (</= 20 Hz) in the cockpits were statistically significantly higher than those in the cabins (17).

Working Hypothesis-3: *infrasound is specifically related to the rate of pericardial thickening.*

The clinical stages of VAD have been defined for a specific type of ILFN-rich job – aeronautical technicians (2). Clinical signs and symptoms, developed by aircraft technicians over 15 years of professional activity, were tallied from medical files in order to determine the progression and evolution of VAD with time. From an initial group of 306 technicians, 166 individuals were selected in accordance with tight selection criteria (2). Of the remaining 140 individuals, the sign or symptom was counted if it appeared in, at least, 50% (70 individuals). Table 2 shows the clinical stages of VAD for individuals working in ILFN-rich environments, as aeronautical technicians.

Table 2: Clinical stages of VAD. Data from a group of 140 aircraft technicians where ILFN exposure time (years) refers to the amount of time it took for 70 individuals (50%) to develop the corresponding sign or symptom (2).

Clinical Stage	Sign/Symptom
Stage I-Mild (1-4 years)	Slight mood swings, Indigestion & heart-burn, Mouth/throat infections, Bronchitis.
Stage II-Moderate (4-10 years)	Chest pain, Definite mood swings, Back pain, Fatigue, Fungal, viral and parasitic skin infections, Inflammation of stomach lining, Pain and blood in urine, Conjunctivitis, Allergies.
Stage III–Severe (> 10 years)	Psychiatric disturbances, Haemorrhages of nasal, digestive and conjunctive mucosa, Varicose veins and haemorrhoids, Duodenal ulcers, Spastic colitis, Decrease in visual acuity, Headaches, Severe joint pain, Intense muscular pain, Neurological disturbances.

In the experience of this team, when ILFN environment is only in the home, or when there is occupational ILFN exposure *plus* some other type of ILFN exposure (residential, recreational, second job, or fetal), the appearance of these signs and symptoms is greatly accelerated.

Working Hypothesis-4: *The effects of ILFN exposure are cumulative.*

In a 1999 study of 236 VAD patients (18), 28 individuals developed tumors, 5 were of which were squamous cell carcinomas of the upper right lobe of the lung (2 in non-smokers), and another 5 had multiple tumors. To date, this team has documented an additional 10 squamous cell carcinomas in the respiratory tract of male VAD patients, occupationally exposed to ILFN (19,20): 8 were located in the upper right lobe of the lung, and 2 in the glottis. Of these 10 individuals, 3 were smokers (2 lung tumors and 1 in glottis), and 2 were heavy smokers (more than 2 packs/day). Except for the 2 heavy smokers (who were not the youngest of the group), all these patients are deceased. One of the surviving patients, an airline pilot, received lung surgery 12 years ago, and remains under tight clinical surveillance, and still smoking (19,20).

Working Hypothesis-5: *ILFN is a mutagenic agent and is responsible for squamous cell carcinomas in the respiratory tract.*
Working Hypothesis-6: *Squamous cell carcinomas of the upper right lobe of the lung strongly suggest excessive ILFN exposure.*

2.3 Acoustical Quantification

It is current practice, in routine noise assessments, to characterize the acoustical environment merely in terms of a dB-level parameter. Usually, frequency distribution analyses are not performed, mainly because they are not required by law. This translates into very unspecific information regarding the type of acoustical environment under study. In the rare cases, information on the frequency content is provided, but usually the lower limiting frequency is 50 Hz, and thus, infrasonic bands are excluded, along with the lower "audible" bands. Subsequently, when individuals develop VAD-related signs and symptoms and documentation on their acoustical environment is requested, it generally contains zero information on the ILFN content of their environments. Hence, matching symptoms to predominance of specific frequency bands is not possible. The situation is such that, even if frequency distribution analyses are obtained, there are no readily available data with which compare them.

The way in which this team has dealt with this problem has been to choose a well-defined acoustical environment that is known to be conducive to VAD, such as the aircraft cockpit. All frequency distribution analyses obtained by this team have been compared to that of the aircraft cockpit, where the ILFN content is known to cause VAD (22-24). As a previously published example (24), see Fig. 1. The difference in dBA (A-weighted measurements, required by law) and dBLin (linear measurements) values can be thought of as the difference between what is *heard* (dBA levels) and what is actually present in the acoustical environment. In other words, in both cockpit and car, one would *hear* the same amount of "noise" but, in the car, the body is exposed to significantly larger amounts of acoustical energy.

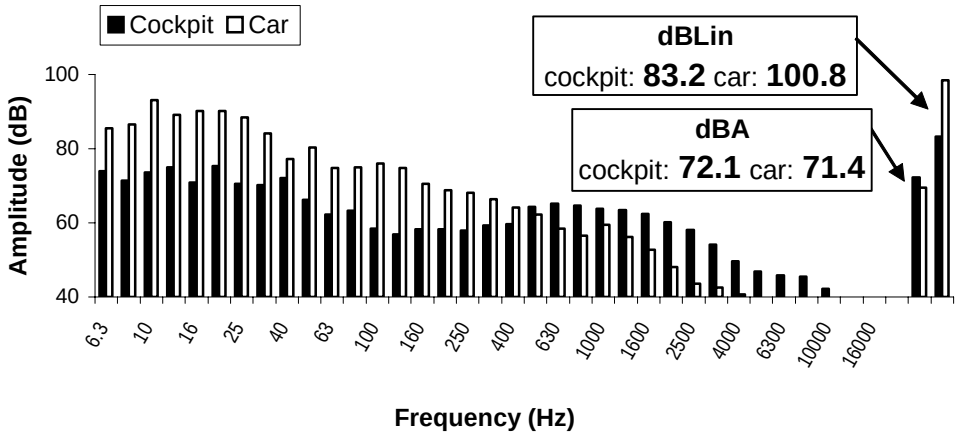

Figure 1: Comparison between the frequency distributions obtained within the Airbus-340 cockpit (black) and within a common passenger vehicle, traveling at 120 km/h, alone on a highway (at 3 a.m.), with windows closed and radio off (white). dBA levels are comparable (72.1 vs. 71.2). dBLin levels are higher than dBA levels, and the difference between both environments is more substantial (83.2 vs. 100.8). In both locations, most of the acoustic energy is concentrated within the lower frequency range (<500Hz). At the more audible frequencies (>1000 Hz), the amplitude is lower, and above 4000 Hz, it is below 40 dB (24).

3 MATTERS TO CONSIDER

The above data raises 3 issues that must be taken into account when considering ILFN dose responses: 1) recovery times, 2) frequency specificity, and 3) ILFN measurements.

3.1 Recovery times

Given the lack of appropriate pharmaceutical intervention for VAD, and the absence of protection against ILFN, mandatory recovery times have been the only resource for patients afflicted with ILFN-induced pathology. The 48-hour continuous exposure (Section 2.1) simulates some types of occupational environments, particularly those associated with ships, oil-rigs and other specific industries where ILFN-rich processes are not constant but are required to operate for several continuous days to be completed. No significant differences were observed after 24 to 48 hours of post-exposure silence, but these images were still not comparable to controls. A more rapid recovery was seen in the 12 hours immediately following ILFN exposure. Presumably, this would indicate that recovery times are not linear, which would also probably mean that exposure vs. effects is also non-linear (25). In practice, if a 48 hour ILFN exposure requires a minimum 12-hour recovery period, it may not be valid to extrapolate that a 24-hour exposure would only require a 6-hour recovery period. It could even be speculated, that a 24-hour exposure would require the same 12 hours for minimal recovery, but in the subsequent 12 hours, a more rapid recovery would be seen.

In terms of VAD, aeronautical technicians with Stage I VAD saw their symptoms disappear, or greatly subside, when on vacation. However, those who had already progressed to Stage II or III did not have similar reactions (2,18). Stage I symptoms are still reversible, while Stage II and III are not.

3.2 Frequency Specificity

Ideally, it would be nice to be able to study the biological effects of pure tones within the ILFN range. To these authors' knowledge, only the team led by Prof. Nekhoroshev (St. Petersburg, Russia) has systematically collected information of this nature (26,27). Regrettably, not all has yet been translated into the English language. Chinese researchers have also been conducting interesting studies at specific tones of ILFN bands (28, for example). These types of studies greatly contribute data for the future establishment of ILFN dose-responses.

Outside the laboratory, acoustical environments do not usually present themselves as single-tone events. Rather, they are composites of many frequency bands, i.e., the acoustical energy is "smeared" across all possible frequencies (See Fig. 1). Here, again, the E&M analogy becomes pertinent: in Nature, light is rarely manifested in terms of single colors, or frequencies. Instead, an array is present, and the same is true of acoustical phenomena. This is why, in studies involving human populations (Section 2.2), information on the dB-level alone is insufficient.

The resonant frequency of a material is the frequency at which the largest amount of energy is absorbed by the material. In the opera singer's analogy, the crystal glass is broken when the singer reaches the resonant frequency of the crystal, where all acoustical energy is absorbed by the glass and, thus, it bursts. Similar events can occur at the cellular level when the resonance frequency of a particular cell-system is achieved. When an acoustical pressure wave impacts on biological (viscoelastic) tissue, it induces a vibratory event at the cellular level which, in turn, is transduced by the mechanical signaling pathways of biological structures (7). Hence, specific resonance frequencies of cellular structures play a critical role in the response of biological tissue to ILFN. Accordingly, information on the frequency content of an acoustical environment is essential for the establishment of ILFN dose-responses.

It is pertinent, here, to refer a 1969 study, conducted by Russian scientists, within the context of the Soviet Space Program. Ponomarkov *et al.* (29) explored the effects of wide-band noise at 105-155 dB on dogs – specific information on frequency content was not provided. After 1.5-2 hours of exposure, the animals were sacrificed. Autopsy results revealed "hemorrhages up to 3 mm in diameter (...) in the lungs" of the animals exposed to about 126 dB, located "beneath the pleura in the form of convex vesicles." The authors observed that as the dB level increased, the number of the hemorrhages also increased, but "they never exceeded 3 mm in diameter." These results speak to a specific effect on this type of tissue that may be more related to a resonance phenomenon (frequency-related) than to event intensity (amplitude, dB).

3.3 ILFN Measurements

As was illustrated by Figure 1, and emphasized in the previous paragraphs, a dB-level measurement does not provide enough information for ILFN dose responses. Acoustical evaluations, as required by law, cannot be the basis for establishing ILFN dose responses – there simply is not enough information contained in a dBA-level measurement to accurately determine the biological effects of ILFN exposure. For the purpose of studying the effects of noise on Public Health (other than hearing impairment), the usage of the A-weighting network should be abolished.

For the same reasons, biomedical and clinical studies should cease to report acoustical environment merely in terms of a measure of amplitude. As can be seen in Figure 1, the dBA level measurements of both cockpit and car are comparable and, therefore, to the scientific community at large, this usually indicates that both these environments are acoustically equivalent. Unless one is exclusively focusing on the amount of "noise" captured by the human ear, cockpit and car are entirely different acoustical environments because their frequency contents are completely distinct. Considering them as equivalent environments is a scientific fallacy. Acoustical environments can only be compared with scientific accuracy if both amplitude (dB-level) and frequency content (in Hertz) are known.

4 DOSIMETRY

Adequate dosimetry of ILFN will be very difficult to achieve until science considers the acoustical spectrum as analogous to the electromagnetic spectrum, i.e., different frequencies have different effects at different amplitudes and on different tissues. Thus, breaking the (lower) acoustical spectrum into infrasound versus audible frequencies is much too rudimentary.

It is proposed that the ILFN (0-500 Hz) portion of the acoustical spectrum be divided into the sub-categories listed in Table 3. Biological tissue is very sensitive to lower frequencies, below 100 Hz (See Section 2.2). Specific frequencies have been known to have a deleterious impact on specific biological tissue, and a 2 Hz exposure can produce different effects than a 5 or 8 Hz exposure (26-28). Dividing the acoustical spectrum in sub-categories would eventually force bio-scientists to specify the acoustical energy within each specific sub-category.

One of the most immediate problems with adequately measuring ILFN is the lack of readily available (and relatively inexpensive) instrumentation. As is well known, much of the monitoring equipment designed to assess physical agents is geared toward assessing the parameters that have been established by legislation. Thus, it is difficult (or much too expensive) to acquire the instrumentation that could adequately measure how long the acoustical energy remains at a certain dB level, for each 1/3 octave band. This would be an ideal parameter for assessing ILFN-induced pathology. Individual dosimeters for ILFN, analogous to individual radiation dosimeters, have yet to be conceived.

Table 3: Proposed subdivision of the lower portion (0-500 Hz) of acoustical spectrum, by 1/3 octave bands.

Sub Category	1/3 Octave Bands (Hz)*	Observations
A_1 A_2 A_3 A_4	0 – 1.6 2 - 2.5 3.15 – 4 5 – 6.3	6.3 Hz is often the lower limiting frequency of standard noise measuring equipment software, although more expensive equipment can collect data well below 6.3 Hz.
B	8 - 12.5	Unusual behaviour in the frequencies of 8, 10 and 12.5 Hz has been detected, in residential, occupational and natural environments (unpublished results).
C	16 – 25	Overlapping the conventional threshold for human hearing (20 Hz).
D	31.5 – 63	Where many machines emit noise, includes the 50 Hz associated with high voltage electrical distribution.
E	63 – 160	Resonance of the thorax.
F	200 – 500	Upper limit, with 250 Hz and 500 Hz already included in audiogram evaluations.

***The 1/3 octave band analysis divides the acoustical spectrum into frequency bands, referred to by their central frequency. Thus, when measuring in 1/3 octave bands, values are obtained for the 1/3 octave frequency bands whose central frequency is, in Hz,: 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315, 400 and 500. Hence, in this Table, the apparent discontinuities in the 1/3 Octave Bands column are due to the way in which science segments the acoustical spectrum.

5 CONCLUSIONS

Appropriate dose responses for ILFN will be impossible to achieve unless the acoustical spectrum is more finely segmented to adequately reflect the dependence of the biological response on the impacting acoustical frequency and amplitude. Within this context, characterizing an acoustical environment merely in terms of a dB-level is entirely unacceptable. By applying “higher-resolution segmentation,” as it were, to the acoustical spectrum, one can begin to compartmentalize frequency bands, and limit their amplitudes. Eventually, accurate and valid ILFN dose responses could be determined.

6 ACKNOWLEDGEMENTS

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