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Low Frequency Noise. What we know, what we do not know, and what we would like to know

by

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Review[1]
Low Frequency Noise. What we know, what we do not know, and what we would like to know

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ABSTRACT
The paper reviews perception of low frequency noise (LFN) and the responses of people to LFN. Sometimes, when there are complaints of LFN and its effects, a specific noise cannot be measured. The possibilities are considered for development of enhanced sensitivity, for alternative (non-aural) receptors at very low frequencies and for false perceptions. The way in which we measure LFN may contribute to the problems.

INTRODUCTION
There is considerable misunderstanding about low frequency noise and infrasound Some of this is due to misleading presentations by scientists 30 or 40 years ago (Gavreau, 1968; Gavreau et al., 1966), which were interpreted selectively by the media in order to give eye-catching news stories. A succession of "reinterpretations" over a period of five or six years led infrasound and low frequency noise to be described in popular texts as a cause of death, whilst also possessing the ability to knock down buildings.(Watson, 1974). This aura of mystery and danger still persists today, deep in the minds of many people, where it waits for a trigger to bring it to the surface. The most recent trigger has been wind turbines.

Although we know a great deal about low frequency noise, there are aspects which we cannot yet explain. We know about how people hear low frequency noise and that some have a low tolerance to it. We believe that low frequency noise may, in general, be more annoying than higher frequency noise, but do not know why this is so. We do not know why some people complain of a low frequency noise which cannot be measured separately from the background noise.

It is also possible that there are subtle effects of low frequency noise on the body, which we do not yet understand.

LOW FREQUENCY NOISE AND INFRASOUND
Low frequency noise is typically the range 10 Hz to 100Hz, although it can be extended an octave at each end of this to give 5Hz to 200Hz. This wider range includes much of what is called "infrasound". There is some confusion over the meaning of the term "infrasound". A popular interpretation is that it is sound of such low frequency that it is below the lower frequency limit of hearing, generally taken to be around 20Hz. A definition of infrasound, found in Standards, is:

> *Acoustic oscillations whose frequency is below the low frequency limit of audible sound (about 16Hz).* (IEC,1994)

However, sound at frequencies below 16Hz is clearly audible if the level is high. The hearing threshold has been measured reliably down to 4Hz for listening in an

[1]Based on a paper given at the 13th International Conference on Low Frequency Noise and Vibration and its Control; Tokyo,October 2008

acoustic chamber (Watanabe and Moller,1990) and down to 1.5 Hz for earphone listening (Yeowart et al.,1967). Fig 1 shows the hearing threshold measurement from Watanabe and Moller between 4Hz and 125Hz together with the low frequency end (20Hz to 200Hz) of the standard hearing threshold (ISO:226, 2003). (The full range of measurements in ISO 226 is from 20Hz to 12.5kHz) There is good correspondence between the two sets of measurements of hearing threshold in the overlap region in Fig 1. Rounded values are in Table I

Table I
Hearing threshold levels

Freq HZ	4	8	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
Level dB	107	100	97	92	88	79	69	60	51	44	38	32	27	22	18	14

There is continuity of perception throughout the frequency range and no evidence for splitting into "infrasound" and" not infrasound" at around 16Hz to 20Hz. However, there is a reduction in slope of the hearing threshold below about 15Hz from approximately 20dB/octave above 15 Hz to 12dB/octave below 15Hz. (Yeowart et al 1967). There is also a change in perception of tonality, occurring around 18Hz. The common assumption that "infrasound" is inaudible is incorrect.

The hearing threshold. The hearing threshold is the median value for otologically normal young adults. Consequently, 50% of subjects have a threshold which is more sensitive than the median and 50% have a less sensitive threshold. The standard deviation of threshold measurement is typically 5 ~ 6dB (Kurakata and Mizunami, 2008; Robinson and Dadson, 1956; Watanabe and Moller, 1990) so that approximately 68% of the population is within ±6dB of the threshold. Half of the remaining (16%) are more sensitive than 6dB below the standard threshold. This includes a very small percentage who are extremely sensitive. Kurakata and Mizunami deal with the frequency range from 2Hz to 50Hz, showing a small frequency dependence of the standard deviation and, for example, that at 50Hz the median value is 44dB and the 5th percentile level is 34dB.

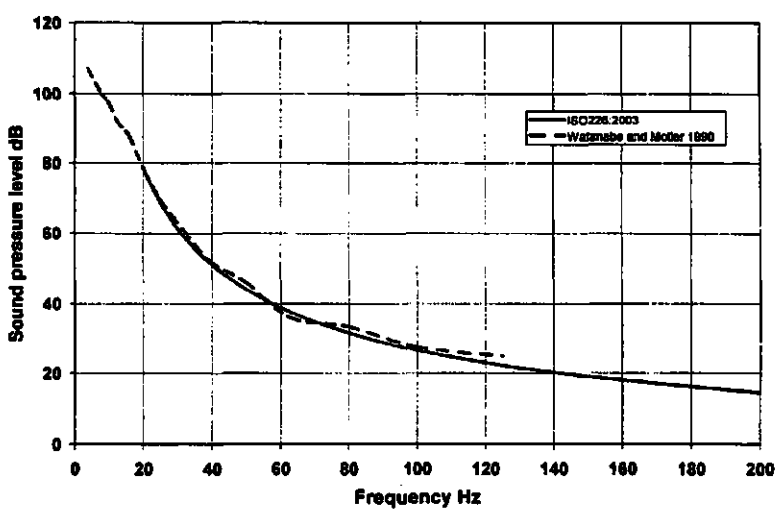

Figure 1 Low frequency hearing threshold

Hearing sensitivity reduces with age, particularly at the higher frequencies. The statistics of age related hearing loss have been standardised by ISO (ISO7029, 2000). The lowest frequency considered in ISO 7029 is 125Hz, which is in the low frequency range, and it is shown that, for example, at this frequency, 25% of 60 year old men may have a more sensitive hearing threshold than the median 18 year old. As it is also demonstrated in ISO 7029 that hearing loss reduces as the frequency reduces, it is likely that a similar condition extends into lower frequencies than 125Hz.

Low frequency hearing thresholds at frequencies lower than those of ISO7029, for otologically unselected 50 - 60 year old adults and for otologically selected young adults, are compared in Table II (van den Berg and Passchier-Vermeer,1999).[2] The 50% level is the median level, or "threshold". The 10% level is a lower threshold below which the most sensitive 10% of the population fall. Comparing 50% levels for 50 - 60 year olds with those of young persons, Table II shows that the older people are assumed 7dB less sensitive at the 50% level than the younger ones, but only 3dB less sensitive at the 10% level.

Table II

Low frequency hearing levels of old and young people

	Otologically unselected population 50 - 60 years old		Otologically selected young adults (ISO 226:1987)	
Frequency Hz	50% Level dB	10% Level dB	50% Level dB	10% Level dB
10	103	92	96	89
12.5	99	88	92	85
16	95	84	88	81
20	85	74	78	71
25	75	64	66	59
31.5	66	55	59	52
40	58	46	51	43
50	51	39	44	36
63	45	33	38	30
80	39	27	32	24
100	34	22	27	19
125	29	18	22	15
160	25	14	18	11
200	22	10	15	7

There are variations in hearing ability at all frequencies, but these differences reduce in the very low frequency region so that, from Table II, there is only a small difference of 3dB between the 10% most sensitive young and old people. Table II shows that, at low frequencies,10% of older people have a 4dB to 5dB lower hearing threshold than the median young person. The well known large differences in hearing sensitivity between old and young people occur at high frequencies, in the kilohertz range, not at low frequencies.

The preceding sections have shown that

- infrasound may be audible, depending on its level
- there is no clear division between infrasound (< 20Hz) and noise of low frequencies (20Hz to 100Hz)
- older people maintain hearing sensitivity at low frequencies, although they often develop high frequency hearing loss.

[2]Note that the ISO thresholds in Table II are based on ISO226:1987, which differs slightly from ISO226:2003

The range from 10Hz to 100Hz may be considered as the low frequency region, with a possible extension by an octave at each end. There is no need to consider infrasound as a "special case". However, audible sounds at the lowest frequencies will be at a high decibel level (Table I).

Sensitisation. It is possible that long term exposure to an unwanted sound leads to enhanced sensitivity. It is known that the brain possesses plasticity and that there is some exchange of function between its parts (Schnupp and Kacelnick, 2002). For example, extensive training in a frequency discrimination task leads to improved discrimination ability and an expansion of the cortical area responsive to the frequencies used during training. Schnupp and Kacelnick quote supporting work on animals as follows:

> *Guinea pigs, trained to associate presentation of a particular pure tone with an unpleasant, but mild, electric shock to the paw, learned to avoid the shock by withdrawing their paw when presented with the tone. Subsequent electro - physiological examination indicated that neurons originally tuned to frequencies on either side of the conditioning frequency had shifted their tuning curves towards that frequency. The shift of frequency tuning meant that more cells in the cortex were available to signal the presence of the conditioned stimulus and that this signal is sensed clearly and unambiguously.*
>
> *Owl monkeys, trained through a reward and denial regime to discriminate a target frequency from different frequencies, were shown to have a shift in neural tuning curves and a sharpening of frequency tuning for the target.*

In humans, there is considerable plasticity in the brain during its early development, requiring appropriate stimuli for proper growth, but plastic adaptation is slower in the adult brain. Two examples of plastic adaptation are:

- London taxi drivers have been shown, through magnetic resonance imaging, to have an enlarged posterior hippocampus compared with control subjects who did not drive taxis.(Maguire et al., 2000). Taxi drivers' anterior hippocampal regions were, however, smaller than controls. Posterior hippocampal volume correlated positively with time spent as a taxi driver, whilst anterior hippocampal volume correlated negatively. The conclusion is that, in order to learn the thousands of routes required for their work, that part of the brain associated with spatial navigation, the posterior hippocampus, enlarged at the expense of neighbouring regions.
- There has been a similar finding for skilled musicians (Pantev et al.,1998). Cortical reorganisation was greater the younger the age at which learning began

The significance of these findings for hearing thresholds is that, if a person listens to an unwanted noise for a considerable period of time, developing an aversion to the noise, they may also develop enhanced hearing sensitivity to this noise. However, one must separate a potential change in hearing threshold from the development of increasing intolerance towards the noise and its source. There may also be an effect of differences in motivation between a desired outcome, such as the development of a new skill, and the undesired outcome of additional annoyance.

In one study there were persistent complaints of disturbance by infrasound from a boiler house (Feldmann and Pitten, 2004), The complaints were of "strong, very low frequency hum, drone, intermittent pulsating, diffuse pressure fluctuations, pain in the legs or in the area of stomach". The annoyance was worse on windy days. However, a narrow band analysis of the noise measured it as 65dB at 1.0Hz, falling by about 30dB per decade to zero dB at 100Hz, whilst hearing threshold tests on the two complainants showed one to have normal and the other to have slightly elevated

hearing thresholds in this frequency region. The median threshold levels in Table I indicate that, as the complainants had normal low frequency hearing, they will not have been detecting the noise through their ears and one is into a complex situation, common with many complaints of low frequency "hums", in which it is difficult to determine whether to assess the noise complaint in terms of low frequency tinnitus, or by the hypothesis of a rare and unknown detection mechanism of extraordinary sensitivity, which cannot be accounted for by the statistical extreme of the low frequency hearing threshold. The complainants described by Feldmann and Pitten may be in the category of "Hum sufferers". See (Demming, 2004) for a study of the Hum.

A few persons with highly sensitive hearing have been discovered amongst the many complainants who have been investigated. For example, one subject had about a 15dB lower threshold than average in the infrasound region. (Yamada,1980) However, it is normal to find that there is little difference between the low frequency thresholds of those who complain of low frequency noise and those who do not (Walford,1983), pointing to the problem being in the "higher centres" of the brain, as illustrated in Fig 2.

This simple model for considering human response to sound identifies three broad stages, detection, perception and response. (Leventhall,1998)

1. The input stimuli enter the detection mechanism, the ear.
2. The stimuli are perceived in the brain as sounds, giving an indication of their frequencies and levels.
3. Response, which is greatly influenced by emotions, follows from perception.

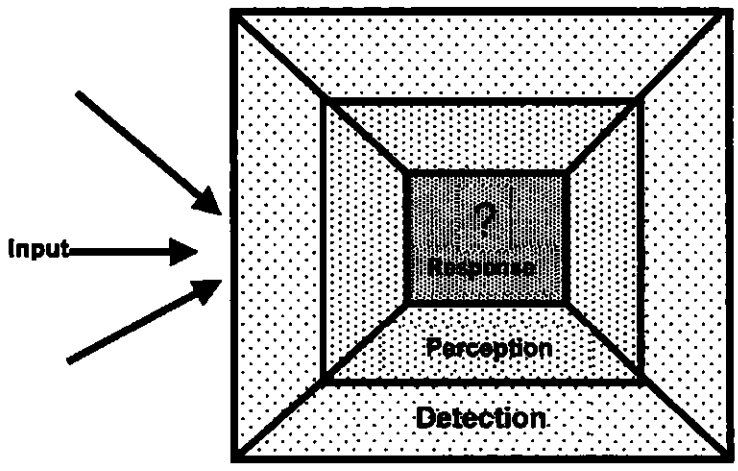

Figure 2 Model of human response to sound input

There is variability at all the stages, but the best quantified steps are detection and perception leading, for example, to the well known hearing contours and hearing thresholds. These may be determined without production of an emotional reaction in the subject. It is the response which displays the widest emotional variations where, for a given low level of unwanted sound, response may vary between "I am not bothered by it" in one person to "it is ruining my life" in another.

We have responsibilities to a group of people, genuinely suffering from perception of noises whose sources have not yet been located. Tracing and controlling noise sources must always be the highest priority, but it is proper to consider some interim means of relieving the problems of complainants. It has been shown that a therapeutic approach may ease the stress which has been produced by

unsolved problems of low frequency noise, so improving the coping capacity of those affected and enabling them to lead an improved quality of life. (Leventhall et al., 2008)

ANNOYANCE BY LOW FREQUENCY NOISE

A summary of annoyance by low frequency noise is given by Leventhall (Leventhall, 2004). An unwanted sound, of any frequency, leads to annoyance, which has origin in a complex of responses, moderated by personal and social characteristics of the complainant. (Belojevic and Jokovljevic, 2001; Benton and Leventhall, 1982; Fields, 1993; Grime, 2000; Guski, 1999; Guski et al., 1999; Kalveram, 2000; Kalveram et al., 1999; Stallen, 1999).

For example, Guski (1999) proposes that noise annoyance is partly due to acoustic factors and partly due to personal and social moderating variables as follows:

> **Personal Moderators:** Sensitivity to noise. Anxiety about the source. Personal evaluation of the source. Coping capacity with respect to noise.
>
> **Social Moderators:** Evaluation of the source. Suspicion of those who control the source. History of noise exposure. Expectations

Noise annoyance in the home is considered as leading to a long-term negative evaluation of living conditions, dependent on past disturbances and current attitudes and expectations. Annoyance brings feelings of disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, hate etc, some of which combine to produce the adverse reaction.

The noise load causes activity interference (e.g. to communication, recreation, sleep), together with vegetative reactions (e.g. blood pressure changes, defensive reactions). It is interference with activity which develops into annoyance and disturbance, whilst prolonged vegetative reactions may lead to effects on health. Personal factors moderate the complainant's complex of responses. Social factors moderate how the complainant interacts with external authorities in attempting to deal with the annoyance. Social factors may also interact with health effects, as some social classes may more readily seek medical assistance. The personal and social moderating factors are so variable that Grime (2000) questions the feasibility of developing a national noise policy.

Annoyance and the "meaning" of noise. Kalveram (2000) points out that much psychoacoustical noise research has limitations, because it is based upon the correlation between annoyance ratings and physical measurements of sound energy, often equivalent level, leading to noise dose. But equivalent level, A-weighted or linear, is only a part of the total process. Noise level and noise dose approaches neglect the "meaning" of a noise. Only a limited number of subjects are protected by the criteria which are developed from these assessments.

Kalveram emphasises the psychological functions of sounds. Annoyance originates from acoustical signals which are not compatible with, or which disturb, these psychological functions. In particular, disturbance of current activities is a primary effect of noise exposure, producing a potential loss of fitness in the subject with respect to those behaviour patterns which permit coping with changes in the environment. Presence of a harmful sensory variable in the environment leads to actions which interrupt current behaviour, in an attempt by the subject to reduce the sensory input. This tests the coping capacity of the individual.

Those who have experienced long-term exposure to low frequency noise may recognise this within themselves, especially if there has been a poor relationship with the noise control officer (Benton, 2007). A few persons are known to have modified their responses to low frequency noise, thereby removing it from the category of a challenge and threat. Others have been helped to make this response modification.(Leventhall et al., 2008)

Most field work on noise annoyance has been where there is a known source, for example air or road transport. The particular circumstances of some low frequency noise problems, where the noise source is not known, adds an additional element to annoyance. Those affected suffer extreme frustration and may find it necessary to identify a possible source, thus enabling themselves to cope through provision of a focus for anger and resentment. Assumed sources have included neighbours, gas pipelines, radio transmissions and defence establishments.

ANNOYANCE MEASUREMENTS

Annoyance measurements are generally of the type described by Kalveram (2000), an attempt to relate annoyance ratings directly to measured noise levels. These measurements are limited in their results, since they deal with only part of the annoyance complex.

Laboratory determinations. There have been a large number of laboratory determinations of annoyance of low frequency sounds, mainly measurements using either 'normal' or 'sensitive' subjects. Stimuli have included tones, bands of noise or specially developed spectra. There is of course, a wide range of possible stimuli, which experimenters have chosen according to their experience of what is required. (Adam, 1999; Andresen and Moller,1984; Broner and Leventhall, 1978b; Broner and Leventhall, 1984; Broner and Leventhall,1985; Goldstein,1994; Goldstein and Kjellberg, 1985; Inukai et al., 2000; Kjellberg and Goldstein, 1985; Kjellberg et al., 1984; Moller,1987; Nakamura and Inukai,1998; Persson-Waye,1985; Persson and Bjorkman,1988; Poulsen, 2002; Poulsen, 2003a; Poulsen, 2003b; Poulsen and Mortensen, 2002). Some of the laboratory studies have used recordings of real noises as stimuli, whilst others have worked with recordings of the actual noises as experienced by subjects in their own work places or homes. (Holmberg et al.,1993; Landstrom et al., 1994; Manley et al., 2002; Mirowska,1998; Mortensen and Poulsen, 2001; Poulsen, 2003a; Poulsen, 2003b; Poulsen and Mortensen, 2002; Tesarz et al.,1997; Vasudevan and Gordon, 1977; Vasudevan and Leventhall, 1982).

Most determinations have been aimed at relating the A-weighted level, or some other derivative of the spectrum of the low frequency noise, to its annoyance. Whilst these are adequate studies, and have shown some general factors in low frequency noise annoyance, they are limited in that their results apply only to the particular noises investigated, often with a small number of subjects. It is unlikely that continued studies of this kind will result in step changes in our understanding of low frequency noise annoyance. However, Poulsen (2003a) is an advance on previous work, as it compares subjective assessments with criteria, which have been developed in some European countries, specifically for assessment of low frequency noise.

EQUAL ANNOYANCE CONTOURS

The main results of this work are as follows. Moller (1987) investigated contours of equal annoyance for pure tones in the frequency range 4Hz to 31.5Hz. The annoyance contours are influenced by the narrowing of the range of equal loudness contours at low frequencies. Moller's results are shown in Fig 3, which gives averages for 18 subjects with normal hearing. The vertical scale is the annoyance rating in terms of the distance marked for the tone along a 150mm linear scale. The lowest frequencies must be at a higher level than other frequencies in order to become audible but, once they are audible, their annoyance increases rapidly. For example, the scale rating range at 4Hz is about 10dB between extremes of annoyance. 8Hz and 16Hz have a 20dB range, whilst 31.5Hz has nearly 40dB range. The 1000Hz comparison, which is for an octave band of noise, has a range of nearly 60dB. These findings are important, as they confirm that the hearing contours are reflected in annoyance, although loudness and annoyance are not necessarily the same.

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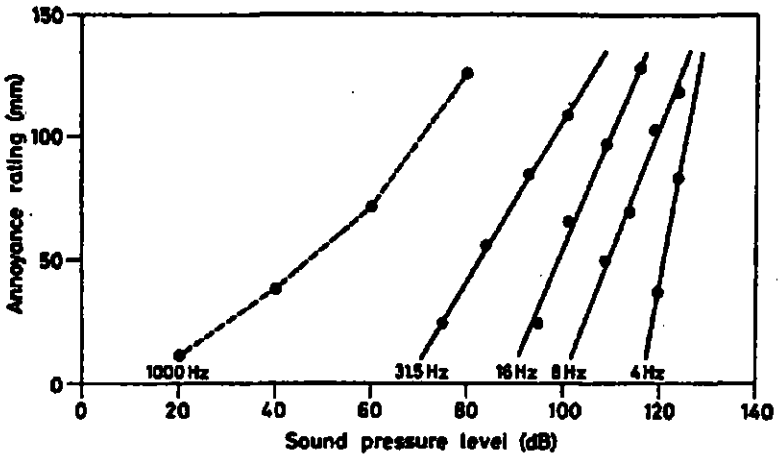

Figure 3 Annoyance rating, showing rapid growth at low frequencies

Subedi et al (Subedi et al., 2005) had similar findings, but used combinations of tones. Inukai et al (Inukai et al., 2005) determined acceptability by noise sufferers of tones in the range 10Hz to 100Hz. They were shown to have low acceptance levels, close to their thresholds.

Individual annoyance functions. Broner and Leventhall (1978) measured individual annoyance functions for 20 subjects using ten low frequency noise stimuli. The psychophysical function was assumed to be a simple power function

$$\Psi = \kappa\varepsilon^{\beta}$$

Where Ψ represents the estimation of psychological magnitude, ε is the stimulus intensity and β a subject-specific exponent. It was shown that there was a wide range of individual exponents, β, from a low of 0.045 to a high of 0.4 and three groupings of individual differences were identified. Previous work at higher frequencies had also shown individual loudness functions (Barbenza et al., 1970) and had posed the question of whether one set of regulations should be applied to all people (Bryan and Tempest,1973).

ANNOYANCE AND THE DBA

A comparison of a band of noise peaking at 250Hz with a band peaking at 100Hz, whilst both were adjusted to the same A-weighted level, showed that the annoyance from the low frequency noise was greater than that from the higher frequency noise at the same A-weighted level (Persson et al.,1985) . This work was subsequently extended (Persson and Bjorkman,1988; Persson et al.,1990) using a wider range of noises, for example, peaking at 80Hz, 250Hz. 500Hz and 1000Hz, confirming that the dBA underestimates annoyance for frequencies below about 200Hz.

For broadband low frequency noise, the underestimate was found to be 3dB for levels around 65dB(Linear) and 6dB for levels around 70dB(Linear). Similar results had been obtained in earlier work (Kjellberg et al.,1984). Two broadband noises were investigated, in which one was dominated by energy in the 15-50Hz range. Twenty subjects compared the two noises within the dynamic range 49-86dBA. At equal A-weighted levels, the noise dominated by the low frequency component was perceived as 4-7dB louder and 5-8dB more annoying.

The energy input to the subjects was, of course, greater for the low frequency noises, as the attenuation of the A-weighting does not measure the full energy, and it might be expected that there would be a greater effect, perhaps suggesting that loudness, assumed related to the A-weighting, differs from annoyance at low frequencies.

UNPLEASANTNESS

The "unpleasantness" of low frequency noise has also been estimated (Inukai et al., 2000; Nakamura and Inukai, 1998). Nakamura and Inukai used a stimulus sound of a pure tone in 20 conditions from 3Hz to 40Hz and sound pressure levels from 70dB to 125dB, with evaluation by 17 subjects. There were four main subjective factors in response to low frequency noise: auditory perception, pressure on the eardrum, perception through vibration of the chest and more general feeling of vibration. Analysis of the responses showed that auditory perception was the controlling factor. That is, although high levels of low frequency noise may produce other sensations, the ear is the most sensitive receptor.

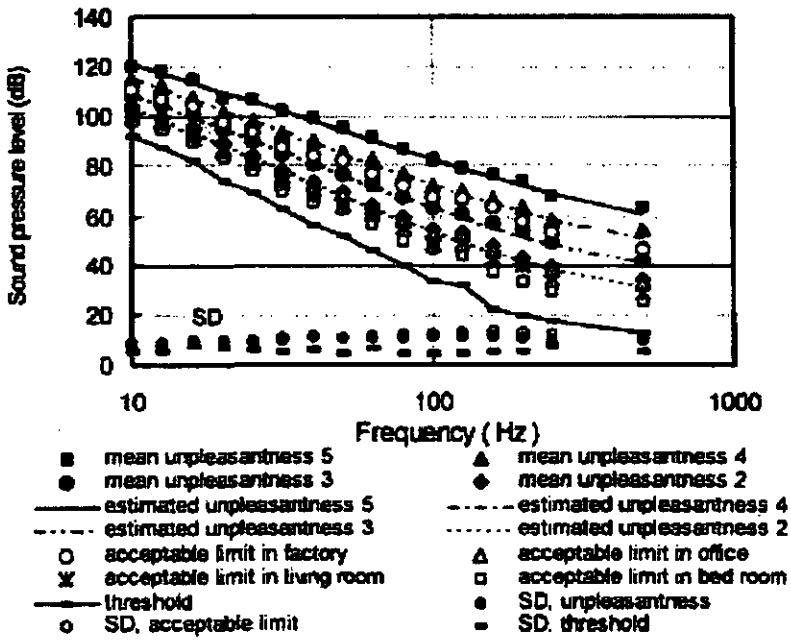

Figure 4 Acceptability and unpleasantness of low frequency noise

Inukai et al (2000) determined "equal unpleasantness" contours for 39 subjects over a tone frequency range of 10Hz to 500 Hz . A verbal scale was used ranging through: *Not at all unpleasant (1) - somewhat unpleasant (2) - unpleasant(3) - quite unpleasant(4) - very unpleasant(5)*. Subjects in a test chamber were asked to assume different home and work situations and adjust the level of a tone to match a level on the scale, as requested by the experimenter. For example if instructed to match to level 4 (*quite unpleasant*), subjects would adjust the tone until they judged that this level was reached. Results are shown in Fig 4 The numbers 1,2,3,4,5 refer to the unpleasantness level. All levels of unpleasantness are approximately linear with a negative slope of 5 - 6dB per octave. The acceptable limits for different locations are all above the hearing threshold in this laboratory setting. For example, the self-adjusted acceptable limit in an assumed bedroom is more than 10dB above threshold, but this might not be replicated for long term exposure at night in a real bedroom.

HIGH INTENSITY EXPOSURE

Experimental subjects in low frequency noise exposures fall into two main groups: people in their homes and people at work. The expectations of these two groups are different. Homes are a place of recreation and sleep. A workplace must be reasonably comfortable and not cause damage. However, military and similar personal have different expectations from those of civilians, and may accept

exposure to high sound levels at all frequencies, especially when they are wearing protective equipment. Much of the early work on high level, low frequency exposure was carried out in connection with the Apollo space program.

The launch vehicles produce their maximum noise energy in the low frequency region. Furthermore, as the vehicle accelerates, the crew compartment was subjected to boundary layer turbulence noise for about two minutes after lift-off. Experiments were carried out, in low frequency noise chambers, on short term subjective tolerance to bands of noise at very high levels of 140 to 150dB in the frequency range up to 100Hz It was concluded that the subjects, who were experienced in noise exposure and wearing ear protection, could tolerate both broadband and discrete frequency noise in the range 1 Hz to 100Hz at sound pressure levels up to 150dB. Later work suggests that, for 24 hour exposure, levels of 120-130dB are tolerable below 20Hz. These limits were set to prevent direct physiological damage (Mohr et al., 1965; von Gierke and Nixon,1976; Westin, 1975). It is not suggested that the exposure was pleasant, or even subjectively acceptable, for anybody except those who might have had a personal interest in the noise. The levels used in these experiments are considerably higher than the exposure levels of people in their homes, arising from environmental, traffic, industrial and other sources. There is an indication of performance decrements at high levels of low frequency noise (Kyriakides and Leventhall, 1977; Mohr et al., 1965; Persson-Waye et al., 1997)

THE RESPONSE OF THE EAR AT HIGH SOUND LEVELS - AURAL PAIN

This is not a hearing sensation, but arises from mechanical displacement of the middle ear system beyond its comfortable limits. Persons with both hearing ability and hearing loss, but with normal middle ears, exhibit aural pain at a similar stimulus level, which is about 165dB at 2Hz, reducing to 145dB at 20Hz. Static pressure produces pain at 175 -180dB, whilst eardrum rupture occurs at 185 - 190dB. (von Gierke and Nixon, 1976). A pressure of 5×10^4 Pa, which is about half atmospheric pressure, is equivalent to 188dB. Eardrum rupture is most likely to occur from unprotected exposure to blast waves.

A sensation of pressure in the ear may occur at levels of 125dB to 130dB, which is about 60dB lower than eardrum rupture, and in the audible range of infrasound and low frequency noise. There is no firm evidence that inaudible levels of noise generally produce ear pressure sensations, although there are wide individual differences in response.

BODY VIBRATION

One effect of high levels of low frequency noise exposure is excitation of body vibrations (Leventhall, 2006; Leventhall et al., 2003; Smith, 2002). A prominent body response is a chest resonant vibration in the region of 50Hz to 80Hz, which occurs at high sound levels, typically above 80dB. The low frequency perception thresholds of normal hearing and profoundly deaf subjects have also been investigated (Yamada et al., 1983) when it was shown that the profoundly deaf subjects perceived noise through the surface of their body, but only at levels in excess of normal hearing thresholds. The threshold of sensation of the deaf subjects was 40-50 dB above the hearing threshold of those with normal hearing up to a frequency of 63 Hz and greater at higher frequencies, for example, about 100 dB greater at 1 kHz, at which level perception was by the subjects' residual hearing. Deaf subjects experienced chest vibration in the same frequency range as subjects with normal hearing. The much repeated statement that "infrasound can be felt but not heard" is not supported by these measurements.

The standard mass-spring model of the body which is used to illustrate the effects of mechanical vibration into the feet or seat, is not appropriate for body vibration generated by low frequency noise. Low frequency noise produces a compressive effect on the whole body, not point excitation By using subjects alternately breathing air and a helium oxygen mixture, it has been shown that the resonant

frequency of chest vibration does not change, so that air cavities in the body are not involved in the low frequency chest resonance, although they may be at higher frequencies. The effect is a compressive vibration of the rib cage. (Leventhall, 2006)

ALTERNATIVE RECEPTORS.

Public concerns on inaudible infrasound possibly arise from confusion of work on subjective effects of low frequency noise, which has been carried out at *high audible levels* in connection with the American space programme (Mohr et al.,1965), with the popular, but incorrect belief, that infrasound is inaudible. There have also been misunderstandings fostered in publications and quasi-scientific books and by objectors to developments, particularly to wind farms. However, the question arises of whether there is a hierarchy of receptors of which the ear is the most sensitive, except at the lower frequencies, when other receptors may come into prominence.

Skin receptors Several vibration and contact detectors, which give us our sense of touch, reside in the skin, covering different frequency ranges. These include the Pacinian corpuscles and Merkel cells (Johnson, 2001). The Pacinian corpuscles are the most sensitive, with a threshold displacement of about 0.001 mm in the region of 200Hz, (Fig 5).. Their sensitivity into lower frequencies reduces at approximately 50dB per decade from the maximum sensitivity. A threshold displacement of 0.001 mm at 200Hz is similar to the particle displacement in air of a 200Hz sound wave of 88dB (0.5 Pa) pressure. Since the particle displacement in a sound wave of constant pressure doubles as the frequency is halved (20dB per decade), inaudible sound waves will not excite Pacinian corpuscles, whose sensitivity into low frequencies reduces more rapidly than the change in the sound wave. Additionally, the vibration of the skin is not the same as that of the sound wave, due to mismatch at the air-skin interface

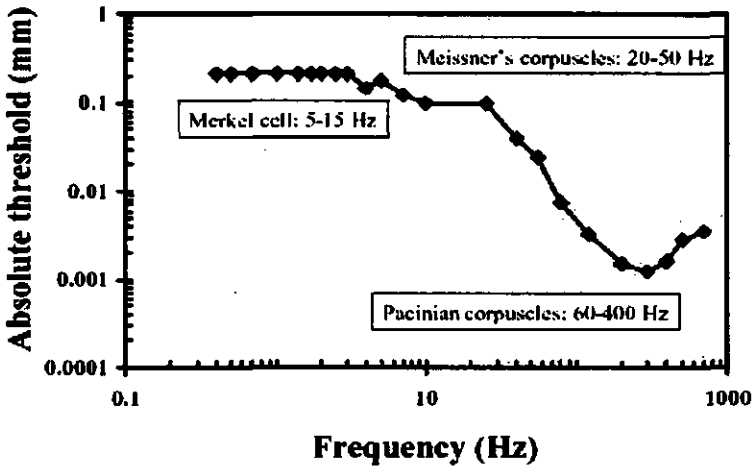

Figure 5 Response of receptor cells in the skin (Jones,2001)

Consider Merkel cells. A particle displacement in air of 0.2mm at 15Hz (threshold of Merkel cells) corresponds to a pressure in the sound wave of nearly 8Pa, or 112dB, which is well above the 15Hz hearing threshold of about 88dB. At 5Hz the pressure in the wave for the same particle displacement is about 10dB lower, or 102dB. This is similar to the median hearing threshold at 5Hz, which is about 105dB, but mismatch between the air and the skin means that the displacement of the skin will be lower than that of the air. In fact, at higher frequencies, the skin is acoustically very reflective, with a measured absorption coefficient of about 0.03 between 1000Hz and 6000Hz (Katz, 2000).

There is little information on transmission of low frequency noise into the human body, although there has been work on sound transmission into the bodies of dead sheep over the range 50Hz to 20kHz, mainly aimed at determining criteria for protection of pregnant women who work in high noise levels (Peters et al.,1993). The body cavity of the sheep was cleaned and filled with water, leaving the organs in place. Internal sound level detection was with a hydrophone, which had been previously calibrated in air, whilst external sound levels were measured with a microphone. Excitation was by a loudspeaker 1 m from the body of the sheep, which was suspended in standing position from a frame. When the different acoustic impedances of air and water are taken into account the attenuation of low frequency acoustic energy from the external air to inside the body is over 30dB.

VESTIBULAR EFFECTS

Another potential mechanism is direct effects on the vestibular system which, by detecting movement of the head, controls our balance system. The canals of the vestibular system are part of the inner ear but, in normal state, are a closed system containing fluid which moves when the head changes position. This movement activates hair cells within the canals, transmitting information to the brain. It has been suggested that infrasound upsets the balance system, leading to disorientation, but for this to occur there must be a mechanism for energy to transfer from the external sound into the vestibular canals. Possible paths are directly through the head or through the ear. Measurement and perception of noise induced vibrations of the body between 20Hz and 50Hz have included measurements on the forehead, which can be taken as representing the vibration of the head. (Takahashi et al., 2002 a; Takahashi et al., 2002 b). It was shown that, for example, for an excitation of 110dB at 50Hz, the vibration acceleration level at the forehead was nearly 100dB re $10^{-6}m/s^2$, which is $0.1m/s^2$ (Fig 6). Converting this to displacement at 50Hz gives $1x10^{-6}$ m. Considering lower frequencies, at 20Hz the acceleration level of the forehead is about 74dB, or an acceleration of $5x10^{-3}m/s^2$.

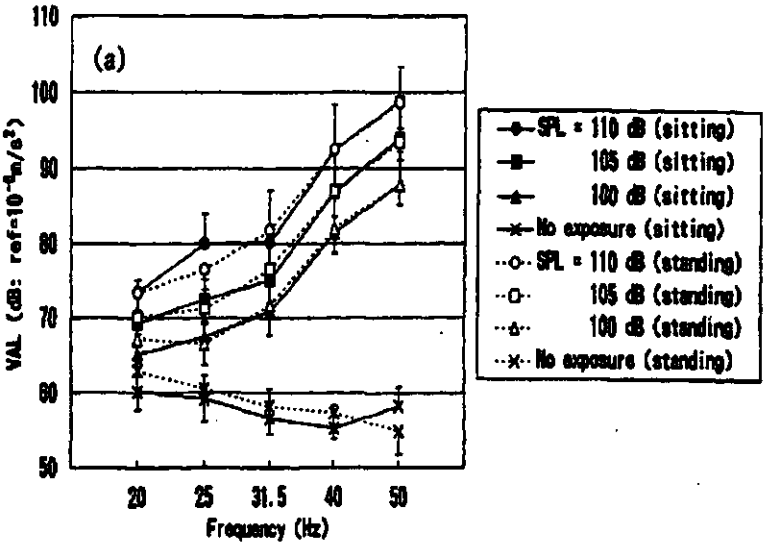

Figure 6 Vibration acceleration level (VAL) at the forehead for excitation by high sound levels. Average and standard deviations of nine subjects. (Takahashi et al)

It is also seen in Fig 6 that, at 20Hz, the response to excitation by a level of 100dB is merging into the inherent forehead vibrations. The levels of the acoustic excitation are all well above the hearing threshold and clearly audible to a person with normal hearing.

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Excitation of the head by external sound waves has been considered by von Bekesy (von Bekesy,1960) and by Hakansson (Hakansson et al.,1994), who also review earlier work. There is variation between subjects, but the lowest skull resonance frequency is in the 900Hz to 1200Hz range, which is outside the infrasound and low frequency region. Von Bekesy determined the threshold of forehead vibrations for hearing by bone conduction between 100Hz and 5000Hz. The threshold at 100Hz is a vibratory displacement of about 10^{-8}m.

This section has shown that it is unlikely that external low frequency noise at levels which are below the threshold of audibility, will have an effect on the vestibular system, which is a less sensitive detector of sound than by bone or air conduction. High levels of low frequency noise and infrasound do produce vestibular excitation, but the sound levels required are greatly in excess of hearing threshold levels (Parker,1976).

THE ABNORMAL VESTIBULAR SYSTEM

The Tullio phenomenon refers to vertigo and similar effects, which are produced in some people when exposed to very high sound levels, sudden movement, unusual exertion or pressure changes. Abnormalities in the vestibular system, such as semicircular canal dehiscence, may enhance symptoms of the type described by Tullio. A review has been given by Banerjee (Banerjee et al., 2005) and a description is given by Curtin.

> *The syndrome appears to be the result of a minute hydraulic phenomenon within the inner ear. When sound vibrations are transmitted from the tympanic membrane by way of the ossicles to the oval window, the stapes acts as a piston, pushing into the perilymph of the inner ear. Fluids are not compressible, and to cause even minute movement of the fluid, there must be a compensatory displacement somewhere in the system that coincides with that of the stapes. In the cochlea, the outward movement of the round window membrane balances the inward movement of the stapes in the oval window. A pressure wave moves through the perilymph of the scala vestibuli and scala tympani to the round window membrane.*
>
> *Normally, the oval and round windows are the only two openings in the hydraulic system of the inner ear. The semicircular canals represent a hydraulically closed system, and there is no substantial movement of fluid in the semicircular canals when the stapes vibrates in response to sound. However, if there is creation of a "third window" in one of the semicircular canals, the hydraulic purity is corrupted, and movement can occur. As the stapes pushes inward, the covering of this third window pushes outward. This causes slight movement of the perilymph. This movement or pressure wave in the perilymph apparently compresses the endolymph within the membranous semicircular canal. The brain interprets motion of the endolymph as movement of the body, and the patient feels dizzy. (Curtin, 2003)*

Consequently, the occurrence of a third window in the inner ear-vestibular system may lead to Tullio effects. Origins of the third window include incomplete development of the vestibular system in childhood, damage from illness or from a blow to the head. The incidence of superior semicircular canal dehiscence, as determined by a study of cadaver temporal bones, led to 0.7% of individuals with dehiscence and a further 1.3% with a very thin bone, which might be predisposed to rupture by trauma. (Carey et al., 2000). One manifestation of the condition is hyperacusis to bone conducted sounds (Schmuziger et al., 2006).

Sufferers hear their eyeballs or joints moving. It is necessary to consider semicircular canal dehiscence in relation to infrasound and low frequency noise. The adverse effects of the condition are generally described as being due to loud sounds, but the sound pressure at the ear from a loud sound in the higher frequencies

is similar to the sound pressure of a quiet sound in the low frequencies (Fig 1). As the natural frequency of the eardrum is well above the low frequency range (von Bekesy, 1960), the ear drum will, ideally and on the assumption that the Eustachian tube remains tightly closed, move with constant displacement down into very low frequencies. The movement of a third window in the semicircular canal could be similar to those at high frequencies, although coupling between the oval window and the dehiscence may have an additional effect. Therefore, there is the possibility that those persons with superior semicircular canal dehiscence might be unduly affected by threshold region or even sub threshold infrasound. Further work is required on this.

The condition will not cause hyperacusis to low levels of external audio frequency noises, although there may be effects at high levels. It should also be noted that vestibular problems are not necessarily experienced by complainants of low frequency noise, whose difficulties are more typically those described earlier i.e. "strong, very low frequency hum, drone, intermittent pulsating, diffuse pressure fluctuations, pain in the legs or in the area of stomach".

SUMMARY ON ALTERNATIVE RECEPTORS

Several receptor mechanisms have been considered: skin receptors, bone conduction in sound fields and abnormalities in the vestibular system. None of these explain the effects complained of by those displaying sensitivity to low frequency noise and infrasound, although vestibular abnormalities may be conducive to some of the effects. The remote possibility of a currently unknown, highly sensitive, individual-specific receptor remains, although there is no direct evidence for this. We must assume that the extreme reactions of some sufferers are conditioned by their individual response, as in Fig 2. The following statement by Berglund and Lindvall must be considered as the current position, until shown to be incorrect.

"..the main sensitive organ for sound at frequencies below 20Hz is within the ear and not in the breast or stomach. There is no reliable evidence that infrasounds below the hearing threshold produce physiological or psychological effects. Infrasounds slightly above the detection threshold may cause perceptual effects but these are of the same character as "norrnal" sounds. (Berglund and Lindvall, 1995)

VIBROACOUSTIC DISEASE (VAD)

Portuguese researchers have adopted the title of Vibroacoustic Disease (VAD) to define a whole-body, multi-system entity said to be caused by occupational or chronic exposure to large pressure amplitude and low frequency (LPALF) noise (>=90 dB SPL, <=500 Hz). (Alves Pereira and Castelo Branco, 2006; Alves Pereira and Castelo Branco, 2007c; Alves Pereira et al., 2004; Castelo-Branco and Alves Pereira, 2004b; Castelo Branco,1999; Castelo Branco and Alves Pereira, 2004a; Ferreira et al., 2004).

The clinical picture involves extra-auditory pathology, such as neurological disturbances, respiratory disorders and cardiovascular problems. Branco reports that the clinical progression is insidious, and lesions are found in many systems throughout the body (Castelo Branco,1999). Some of the findings, such as extracellular matrix changes, appear to be specific to this disease. Others, such as cognitive impairment, are common in different types of stress-induced pathology. Having reviewed 140 males who worked around aircraft on the ground with engines operating, carrying out daily aircraft run-ups, Castelo Branco classified VAD with respect to the time it took for 50% of the population to acquire the relevant signs or symptoms. Stage 1, mild signs (behavioural and mood associated with repeated infections of the respiratory tract e.g. bronchitis) - 2 years; Stage ll, moderate signs (depression and aggressiveness, pericardial thickening and other extra-cellular matrix changes) - 5 to 9 years; Stage lll, severe signs (myocardial infarction, stroke, malignancy, epilepsy, and suicide) 11 to 15years.

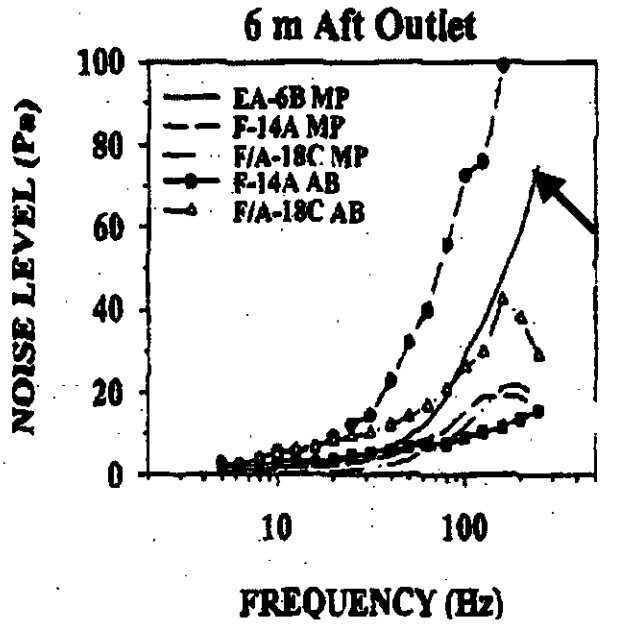

Figure 7 Noise Levels in pascals 12.8m from the aircraft centre line and 6m behind the engine outlet. 64Pa = 130dB (Smith, 2002)

The concept of VAD was developed from Castelo Branco's observations that a technician, working around military aircraft with engines operating, displayed disorientation. Sound levels near aircraft are very high. In a study of body vibration resulting from exposure to noise levels from ground running aircraft, Smith showed that the typical engine spectrum of carrier based combat aircraft peaked at frequencies above 100Hz with noise levels from 120 to 135dB near to the plane, as in Fig 7, which includes the EA6B Skywarrior (Smith, 2002). The aircraft in Castelo Branco's initial investigations, the EA3B (Skywarrior) (Alves Pereira and Castelo Branco, 2006; Alves Pereira and Castelo Branco, 2007c), was not included in Smith's investigations, but was also designed as a carrier based combat aircraft, and it may be assumed that the noise exposure of the workers who displayed VAD symptoms were similar to exposures reported by Smith. Measurements made on other aircraft in Portugal, down to a lowest frequency of 20Hz, also showed high exposures with the greatest levels occurring in the kilohertz regions. (Bento Coelho J L et al.,1999) . The highest levels were 110 to 120dB, dropping to 60 -70dB at 20Hz, This is below the hearing threshold at 20Hz, which is nearly 80dB. Maintenance workers employed by the aviation industry are exposed to high noise levels and those with more than 10 years exposure may, according to Castelo Branco, develop VAD.

In its initial stages (2 year exposure) VAD is associated with an increase in respiratory infections. Investigations have shown that laboratory mice exposed to LPALF noise also developed immunological changes, in agreement with the human studies. Long-term exposure of rats to high levels of low frequency noise caused focal thickening of the intima of the aorta and femoral arteries, disruption of the internal elastic lamina and proliferation of smooth muscle cells in the intima of 70% of the rats. (Dos Santos et al., 2002)

The symptoms presented by those with long term exposure to noise from ground running aircraft have not been generally accepted as resulting only from the noise in this complex environment, which also includes exposure to chemicals from the jet engine. The opinion of one commentator is:

> *"Vibroacoustic disease" remains an unproven theory belonging to a small group of authors and has not found acceptance in the medical literature. (von Gierke, 2002)*

VAD was initially defined for large pressure amplitude low frequency noise (LPALF) noise from 0 to 500Hz at levels greater than 90dB - although in the vicinity of aircraft this often occurred in the presence of much higher amplitude high frequency noise. Recent stimulation of public concerns on infrasound and low frequency noise have led the VAD research group to state that low levels of these noises are also a potential cause of VAD. In particular, objectors to wind turbine developments have focused attention on infrasound and low frequency noise from wind turbines and, with the backing of the VAD research group, claimed that wind turbine noise leads to VAD. (Alves Pereira and Castelo Branco, 2007b). The transition from noise levels of 90dB or above, with most of its energy in higher frequencies, to inaudible wind turbine noise levels of 40dB to 60dB in the infrasound region as a cause of VAD is, in effect, a new hypothesis and it is the responsibility of its proponents to support this with evidence, which has not yet been done. Epidemiological studies have not been made. On a noise dose basis, it would take 100,000 years of exposure at 50dB to equal the noise dose of one year of exposure to 100dB.

SUMMARY ON VIBROACOUSTIC DISEASE

To suggest that infrasound levels in the region of 50dB are an agent of disease is a regression to the 1970's media-hyped view of infrasound, which considered only its presence and not its levels.[3] Nevertheless, we must be aware that uncomfortably high sound levels at high frequencies may be sub-threshold levels at infrasonic frequencies. Similarly, we must question whether the levels of around 50dB, which occur, for example, from wind farms in the infrasonic and very low frequency region, would be considered as an agent of VAD if they occurred in the 100Hz to 500Hz region. The attribution of dangerous properties to low levels of infrasound continues unproven, as it has been for the past 40 years.

ASSESSMENT OF INFRASOUND AND LOW FREQUENCY NOISE

The World Health Organization has recognised that the general assessment measures for environmental noise are deficient for evaluation of disturbance from noises with large low frequency components (Berglund et al., 2000).

Unwanted noises, including infrasound and low frequency noise, do have stress related effects on hearers, as shown in "The Hum", a noise of unknown origin, not normally identifiable by sensitive measuring equipment, but causing considerable problems to a small number of people, for whom it leads to a stressful, poor quality of life. The Hum is heard in a number of developed countries and remains an acoustic mystery, such that its origin may not be acoustic, although the sensation which it produces is described as that of a sound. (Leventhall et al,, 2003) (Demming 2004).

A number of countries have developed criteria for limiting low frequency noise, which are summarised in (Leventhall et al., 2003; Moorhouse et al., 2004) and shown updated in Fig 6.. The methods of application of the criteria differ and reference should be made to the original documents for this information, but criteria are similar over most of the range. In the low frequencies, criterion levels should be lower than the ISO 226 median threshold in order to allow for those people with greater sensitivities. (Fig 6 continues the ISO 226 threshold into lower frequencies as in Fig 8.)

[3]"The silent killer all around us", London Evening News, 25 May 1974 . "The silent sound menaces drivers" - Daily Mirror, 19 October 1969. "Danger in unheard car sounds" The Observer, 21 April 1974.

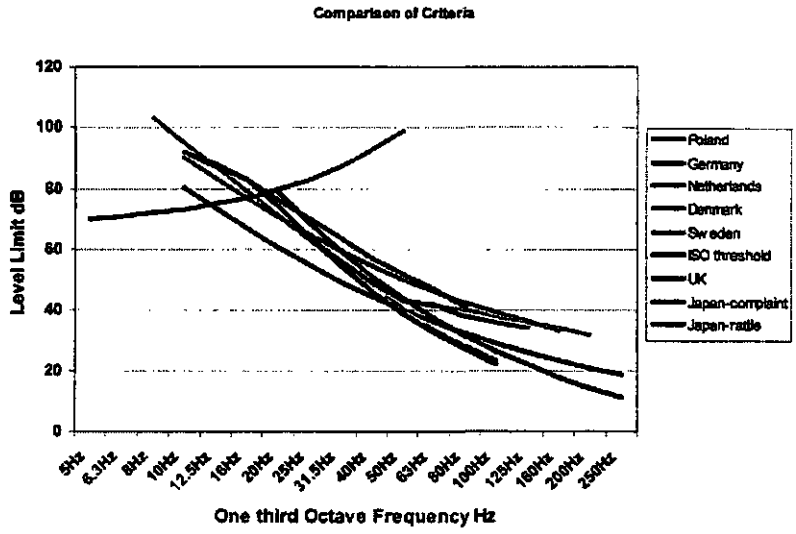

Figure 8 National criteria for low frequency noise

LOW FREQUENCY NOISE AND STRESS

Any persistent and unwanted sound, low frequency or high frequency, is a stressor. Unfortunately, conventional methods of dealing with environmental noise stressors are A-weighted, which means that the presence of disturbing low frequency noise may not be detected. This absence of a measurement requirement for noise control officers to pursue the source of a low frequency noise, in turn leads to long term stress effects in the low frequency noise complainant.

Stresses may be grouped into three types: cataclysmic stress, personal stress and background stress. Cataclysmic stress includes widespread and devastating physical events. Personal stress includes bereavements and similar personal tragedies. Cataclysmic and personal stresses are evident occurrences, which are met with sympathy and support, whilst their impacts normally reduce with time. Background stresses are persistent occurrences, which may become routine elements of our life. Constant low frequency noise has been classified as a background stressor (Benton and Leventhall,1994; Leventhall et al., 2003). Whilst it is acceptable, under the effects of cataclysmic and personal stress, to withdraw from coping with normal daily demands, this is not permissible when exposed to a low level background stress, although inadequate reserves of coping ability lead to the development of stress symptoms. In this way, chronic psychophysiological damage may result from long-term exposure to an audible, low-level low frequency noise, which is left uncontrolled, despite complaints.

Many sufferers are, understandably, very resentful of the noise and of those who might be responsible for the source, developing aggressive feelings towards anybody whom they suspect, often their neighbours. They become tremendously stressed and aggrieved by their situation. However, whilst sourcing and controlling the noise must always have top priority, it has been shown that established techniques of stress management may have an ameliorating effect on sufferers' reactions, so leading to an improved quality of life. (Leventhall et al., 2008).

Whilst it may be too simplistic to attribute all subjective effects of low frequency noise to the stress which it produces, the symptoms complained of may also occur in other people who do not associate the symptoms with a noise. This is considered later.

FALSE PERCEPTIONS

It is possible that some problems are incorrectly attributed to low frequency noise Complaints sometimes occur where it is not possible to measure a noise separately from the background noise. This then intensifies the problem as the complainants feel that they are not believed when their complaint is described as "not valid." We have to consider whether there are non-acoustic stimuli, which would not be measured by a sound level meter, but which might result in a sensation of sound. Potential sources of some of the effects, which, in these circumstances, might be blamed on low frequency noise have been described previously. (Leventhall et al., 2003) The effects include tinnitus, electromagnetic waves, and synaesthesia.

Tinnitus is a subject of much continuing study. (Henry et al., 2005). Henry explains that tinnitus may be of neurophysiological or somatic origin. Somatosounds usually have vascular, muscular, respiratory or temperomandibular joint origin. Whatever the cause, the signal is processed and perceived as an auditory sensation.

Developments in the hearing of electromagnetic waves since this previous publication (Leventhall et al., 2003) include the following:

- The US Secretary of the Air Force has taken out a patent on use of the microwave auditory effect as a means of communication[4]. The process includes preconditioning of the microwave signals to improve information carried in the pulses. An earlier patent had proposed using a controlled configuration of pulses to transmit information direct to the brain and cochlea[5].
- Recently, the Sierra Nevada Corporation is reported as looking for US Government funds to develop a microwave ray gun, producing disabling noises in the head through the microwave auditory effect[6].

However, normal electromagnetic waves in the environment are too weak to cause hearing sensations.

Developments in the study of synaesthesia have confirmed that a transfer between sensory inputs can lead to a synaesthetic sound as a result of a visual input (Hubbard 2008; Saenz and Koch 2008)

The remainder of this section considers medically recognised syndromes which are similar to the complaints of some low frequency noise sufferers, but which are not normally associated with exposure to noise, although stress from any cause predisposes to the syndromes.

The "exploding head syndrome" leads to awakening, giving a "sensation of a loud sound in the head", which is often over by the time the sufferer is fully awake. For example

> *A 43-year-old woman was seen with a 5-month history of a noise in her head On an almost nightly basis, as she was falling asleep, she would hear a loud noise like "electrical current running" lasting a second. Sometimes her whole body would shake for a second afterwards. Very occasionally, she would have an associated flash of light. Frequently, a second episode of the loud noise occurred shortly after the first (Evans 2006)*

Another patient had exploding head syndrome followed by sleep paralysis for six seconds. Episodes are most common in the middle aged and old, slightly more common in women that in men. After-effects include extreme anxiety, palpitations or strong heartbeat.

[4]Patent no. US 6587729; 2003 Apparatus for audibly communicating speech using the radio frequency hearing effect

[5]Patent no. US 4877027: 1989 Hearing system

[6]http://technology.newscientist.com/article/dn14250-microwave-ray-gun-controls-crowds-with-noise.html

In a study of uncommon headaches Evans noted scalp pain and a burning sensation in one ear. (Evans, 2006). Le Fanu studied a wide range of syndromes,.(Le Fanu, 2002) . Amongst these he found general muscle stiffness, pains, body heat or chill, sore ear, throbbing ear, nausea, pounding heart/vibrations, nocturnal electric shock. The causes of the syndromes were not clear.

Some of the effects described above are similar to those reported by complainants of low frequency noise. It is not known whether, in the case of low frequency noise, the sufferers are experiencing some of these syndromes and attributing them to direct effects of the noise.

LOW FREQUENCY NOISE AND SOMATOFORM DISORDERS[7]

> *Somatization is where mental factors such as stress cause physical symptoms. Somatoform disorders are a severe form of somatization where physical symptoms can cause great distress, often long-term. However, people with somatoform disorders are usually convinced that their symptoms have a physical cause.* (See http://www.patient.co.uk/showdoc/27000243/)

In somatization, a problem which has a mental or emotional cause is expressed as physical symptoms. These symptoms include: *"headache, fatigue, joint pains, nervousness, sleep problems, burning of the eyes, nausea, dizziness, weakness, memory problems, gastrointestinal symptoms and respiratory symptoms"* (Bailer et al., 2005). Typical patients are well educated, middle aged and about 70% female.

Again there are similarities between these symptoms and those complained of by low frequency noise sufferers. There is no evidence that those hearing noise which cannot be measured have a somatoform disorder. However, a possible sequence is that noise leads to stress, which then causes somatoform disorders.

The problem of complaints of noise, and the resulting physical effects from low frequency noises which cannot be measured, is a very difficult one. It is possible that we do not measure noise in the best way. Low frequency noises, especially those from a distant source are fluctuating continuously. However, we measure an average level over a period of time, so losing information on fluctuations, which may play an important part in the subjective effect of the noise. Moorhouse et al have suggesting including fluctuations in the assessment of low frequency noise. (Moorhouse et al., 2007). This is an area for further work.

This section has shown that there are a number of non-acoustic problems which might lead to the perception of a noise, but are not caused by noise. Attempts to measure a noise will either fail or lead to false conclusions about an existing noise.

SOME FINAL QUESTIONS

This review of low frequency noise and its effects leaves some unanswered questions, towards which future work might be directed.

- Is the ear the most sensitive receptor to low frequency sound in the body?
- Alternatively, is there a receptor mechanism in the body which is more sensitive than the ear at low frequencies? If so, what is the mechanism?
- Are levels of infrasound below hearing threshold potentially harmful? If this is true, are there safe levels? -
- When people complain about noise which cannot be measured, is it because they are disturbed by fluctuations in the background noise?
- Can fluctuations in the background noise level turn a noise, which has an average level below the hearing threshold of a listener, into a nuisance?
- If fluctuations are combined with the lowest sensitivity of the hearing threshold (e.g. three standard deviations below the median) can people hear noises which have a measured average value so far below the hearing threshold that we might consider them inaudible?

[7]Somatoform disorders are sometimes linked with Idiopathic Environmental Intolerance, which is normally considered to be a hypersensitive response to exposure to chemicals, electromagnetic radiation or other environmental factors, but not to noise.

- Does the way in which we measure low frequency noise hide some of its disturbing characteristics?
- Considering the normal distribution of the hearing threshold, why are there not more complaints of low frequency noise?

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