The effects of industrial airborne ultrasound on humans

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Reported physiological effects resulting from the exposure of small animals to ultrasound cannot be transposed directly to man. There is no evidence of permanent biological changes, including hearing loss, as a result of normal industrial exposures to pure ultrasound, although some effects may occur as a result of experimental laboratory exposures. The high levels of high-frequency audible sound which accompany many industrial processes, particularly those producing cavitation, may cause unpleasant subjective effects, including headaches, nausea, tinnitus, and possibly fatigue in persons without hearing loss at those frequencies.

Introduction

Ultrasonic devices are now widely used in production industries for a variety of processes, including drilling, dicing, soldering, cleaning, welding plastics, emulsification, mixing liquids, initiating free-radical chemical reactions and so on. Relatively low ultrasonic frequencies in the range 20–40 kHz are generally employed for mechanical reasons, although small apparatus has been encountered operating at a frequency as low as 16 kHz. Measured sound pressure levels at the operator's working position rarely exceed 110–120 dB.[1-3] An earlier bibliography was published by Cordell in 1968.[4]

These sources invariably emit airborne noise, not only at the operating frequency and its harmonics, but also at sub-harmonics which may be audible. Furthermore, processes involving liquids, (eg, washing, mixing and using a liquid suspension of abrasive powder) are accompanied by the phenomenon of cavitation. This is thought to involve the formation of bubbles of gas previously held in solution around nuclei, such as the abrasive particles in suspension or dirt on objects being cleaned. The bubbles grow until they reach a resonant size, when they oscillate with an increasing amplitude until they implode. Non-linear radial and surface oscillations of the gas-filled bubbles may be responsible for more tonal noise, and the violent collapse of cavities is responsible for the generation of high levels of random noise at frequencies of approximately 3 kHz upwards.[5]

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Ultrasonic frequencies used in medicine for cell destruction are generally in the range 1–3 MHz and for diagnosis in the range 1–20 MHz. Diagnostic exposures were not considered likely to be potentially harmful by Hill.[6] As these frequencies do not appear to have found widespread industrial application yet, they will not be considered further.

Historical review

When jet aircraft were introduced the term 'ultrasonic sickness' was coined[7,8] to cover a complex of symptoms which included excessive fatigue, headache, nausea, vomiting, etc, exhibited by personnel working in their vicinity. Allen, Frings and Rudnick[9] observed a loss of the sense of equilibrium or slight dizziness on exposure to intense (160–165 dB) high-frequency audible sound, and unsteadiness and dizziness have been reported in personnel exposed without ear defenders and at close range to the noise from the air intake of jet engines.[10,11] The latter authors suggest that this might be due to vestibular disturbances caused by intense acoustic stimulation. In any case, published analyses of jet engine noise show that radiated airborne ultrasound is not present at significant intensities. As ultrasonic frequencies are rapidly absorbed by air, intense ultrasound would only be encountered in regions where approach was normally barred by safety considerations.[12,13] Finally, Parrack[14] stated that 'ultrasonic sickness' was 'largely psychosomatic in origin', although, of course, the other effects had been real enough.

Then followed a period when the possibility of effects from exposure to airborne ultrasound was dismissed. Davis, Parrack and Eldredge[15] stated that there was no evidence that airborne ultrasound constituted a hazard to the hearing, and, in general, high-intensity audible noise was potentially more hazardous. Parrack[8] concluded that there was no hazard from laboratory sources of airborne frequencies.

A note of caution was introduced in the mid 1950s. Crawford[16] reported that the original laboratory workers had suffered unusual fatigue, loss of equilibrium, nausea and headaches which persisted after the exposure had ceased, and 'some loss of hearing in the upper audible frequencies', although this was not substantiated by audiometry and was probably based on purely subjective observations. Systematic research into the biological effects of ultrasound was started in Russia in the late 1950s,[17] but some of the translations and reviews available in the West should be viewed critically as effects observed with liquid or solid coupling to the ultrasonic source have apparently been attributed to airborne ultrasound.

There have been a number of audiometric temporary threshold shift investigations involving laboratory[14,18,19] and industrial[20] exposure, and at least one retrospective permanent threshold shift investigation.[3] Subjective effects have been correlated with measured exposure levels by Skillern[21] and Acton and Carson.[20] Finally, a number of exposure criteria for the prevention of both auditory and subjective effects have been proposed, and these do not differ widely.[1,2,17,22,23]

Physiological effects

One difficulty in reviewing the physiological effects is to be certain that the exposure was to airborne ultrasound. Another difficulty is that many, often bizarre effects have been reported without the exposure level being quantified.

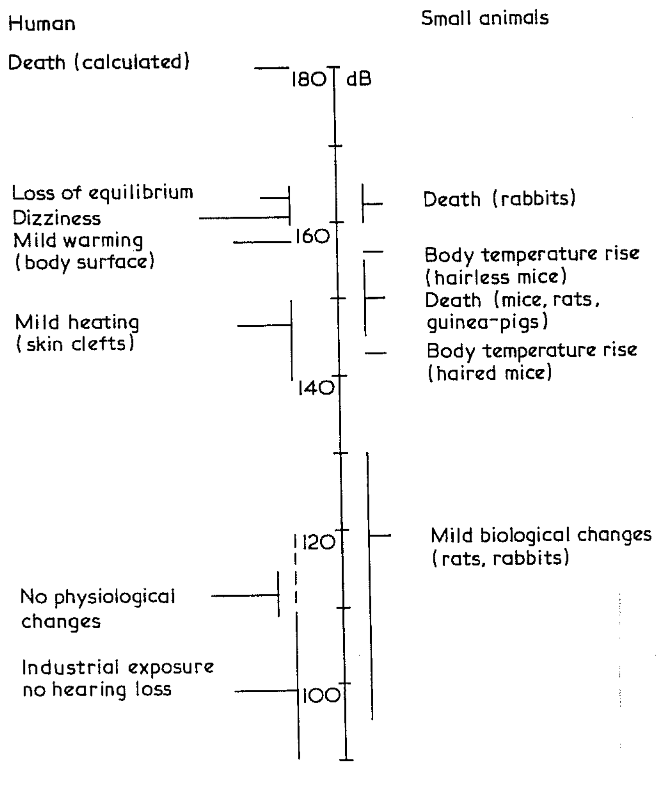

Fig.1 Physiological effects of ultrasound

Consequently, this section of the review has been limited to references which specifically stated exposure conditions, and these have been summarized in Fig. 1.

In the case of airborne ultrasound, the acoustic mismatch between the air and tissue leads to a very poor transfer of energy. The effects on small fur-covered animals are more dramatic because the fur acts as an impedance matching device; they have a greater surface area to mass ratio; and they have a much lower total body mass to dissipate the heat generated than man. Furthermore, the lower ultrasonic frequencies may well be audible to these animals, and the exposures have been to high sound pressure levels. Therefore, the effects on small laboratory animals cannot be extrapolated directly to the human species.

Mild biological changes have been observed in rats and rabbits as a result of prolonged exposure to sound pressure levels in the range 95–130 dB at frequencies from 10–54 kHz. Where the sound was audible to the animals, these represented relatively high sensation levels and the biological changes were typical of any stress condition in many cases. Actual body heating in mice was not measured until a level of 144 dB at 18–20 kHz was reached. With hairless mice the corresponding level was 155 dB, indicating the role of the fur in absorbing energy.[27] The deaths of mice and guinea pigs as a result of exposure to a level of 150–155 dB at 30 kHz[10] of rats and guinea pigs to 144–157 dB at 1–18.5 kHz,[28] and of rabbits to 160–165 dB at 22.5 and 25 kHz[27,29] have been reported also.

In man there are reports of both a drop[30] and an increase in the blood sugar level[31] and electrolyte balance changes in the nervous tissues[32] as a result of exposure to ultrasound, although neither sound levels or frequencies were reported. However, Batolska et al[33] rightly pointed out that many of the effects attributed to ultrasound are also typical of exposure to other physical and toxic conditions at their places of work, and conclusions should not be drawn without comparison of results with a control group.

Grigor'eva[2] failed to find any significant physiological changes as a result of a one hour exposure to 110–115 dB at 20 kHz in a comparison with control subjects.

Slight heating of skin clefts was observed by Parrack and Perret[34] as a result of exposure to ultrasound at levels of 140–150 dB. At 159 dB there may be a mild warming of the body surface.[35] Loss of equilibrium and dizziness occurred at levels of 160–165 dB at 20 kHz.[9] The calculated lethal dose for man is at least 180 dB.[14]

Auditory effects

The ear constitutes an efficient impedance matching device for high-frequency airborne sound, and it seems likely that any hazard from airborne ultrasound will manifest itself initially as a hearing loss or an associated psychological effect.

An investigation to determine if the noise from industrial ultrasonic devices caused auditory effects was described by Acton and Carson.[20] The hearing threshold levels of 16 subjects (31 ears) were measured in the frequency range 2–12 kHz before and after exposure to the noise over a working day. No significant temporary threshold shifts were detected (Fig. 2). On the assumption that if a

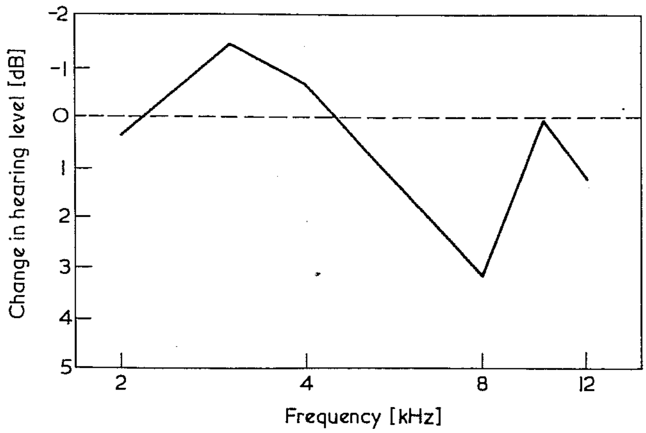

Fig.2 Temporary threshold shift due to industrial exposure to sound[20]

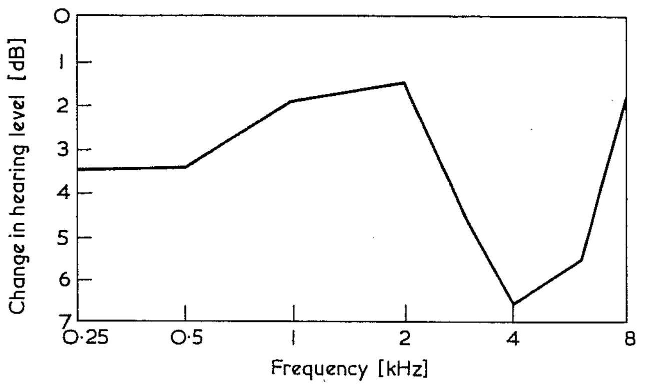

Fig.3 Permanent threshold shift due to industrial exposure relative to control group[3]

noise exposure is not severe enough to cause a temporary threshold shift, then it cannot produce permanent damage, it was concluded that hearing damage due to exposure to the noise from industrial ultrasonic devices is unlikely. A parallel retrospective investigation by Knight[3] on a group of 18 young normal subjects using ultrasonic devices showed a median hearing level within 5 dB of that of a matched control group of hospital staff except at 4 kHz where the departure was 7 dB (Fig. 3). It was concluded that it would have been difficult to attribute this exposure solely to ultrasonic radiation. In addition, no abnormal vestibular function test (caloric test) results were found.

Some temporary threshold shifts have been reported as a result of exposures to ultrasound under laboratory conditions. The exposure conditions reported by Parrack,[14] Dobroserdov,[18] and Smith[19] are shown in Fig.4.

The exposures used by Dobroserdov were at high audible frequencies, while those by Smith contained high audible frequency noise. The results due to Parrack are interesting in that he exposed subjects to discrete frequencies mainly in the ultrasonic region, and measured temporary threshold shifts at sub-harmonics of one half of the fundamental and occasionally at lower sub-harmonic frequencies as a result of five minute exposures to discrete frequencies in the range 17–37 kHz at levels of 148–154 dB. Sub-harmonic distortion products have been reported in the cochlearmicrophonic potentials of guinea pigs.[36] and have also been monitored in the sound field in front of the eardrum using a probe-tube microphone.[37] They were believed to result from non-linear amplitude distortion of the eardrum, and they appeared at a magnitude of the same order as that of the fundamental. This observation may help to explain Parrack's findings.

Many sources of ultrasound, and particularly processes involving cavitation, produce substantial levels of noise in the high audible range. Reported auditory effects can often be explained in terms of the audible noise only, and these references have been omitted deliberately.

Subjective effects

It has been mentioned already that early laboratory workers reported suffering unusual fatigue, loss of equilibrium, nausea, and headaches which persisted after the stimulation had ceased, as a result of their exposure to airborne ultrasound. Complaints of fatigue, headaches, nausea and tinnitus are frequently made by the operators of industrial ultrasonic devices, but their exposure does not seem to be sufficiently intense to cause loss of equilibrium. Observers entering the sound field for shorter periods often experience an unpleasant sensation of 'fullness' or pressure in the ears.

It has been shown that these subjective effects are due to the high levels of high-frequency audible noise usually produced as a by-product of industrial ultrasonic processes, and especially those involving cavitation.[20] Skillern[21] attempted to correlate these effects with frequency and erroneously concluded that the ear was sentitive to a narrow band of frequencies centred on 25 kHz. Examination of his data shows that all frequency spectra he quoted as producing effects contained high levels of high-frequency audible noise as well as an ultrasonic component at about 25 kHz.

The effects are often only reported by young females in exposed populations, but Acton and Carson[20] showed that this was a function of auditory threshold. Males employed industrially often have high-frequency hearing losses, probably due to noise-induced hearing loss and presbycusis, or 'sociocusis'. The effects were not considered to be psychsomatic in origin or due to hysteria.

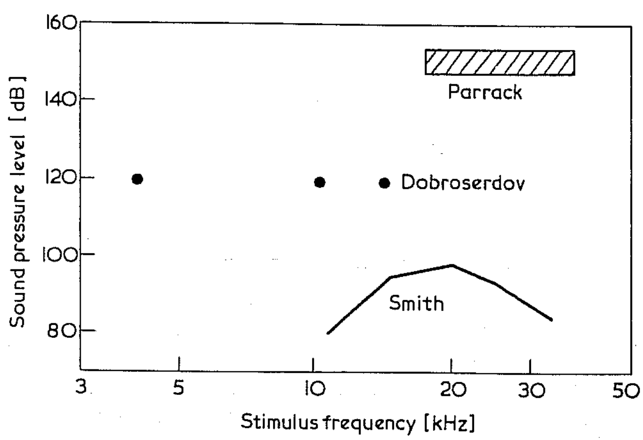

Fig.4 Laboratory exposures producing temporary threshold shifts

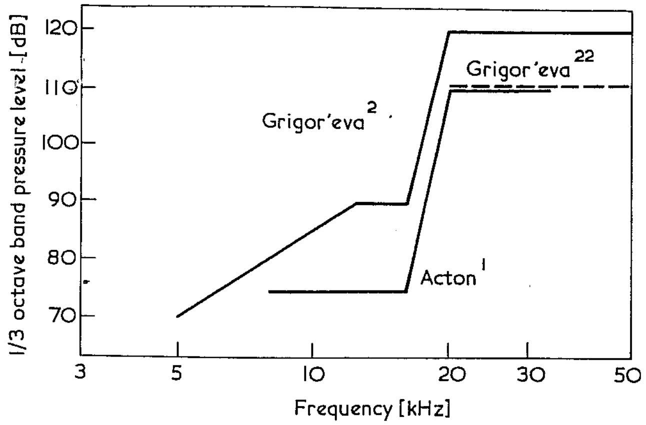

Fig.5 Exposure criteria for ultrasound

Exposure criteria

Unlike audible noise the area of ultrasonic noise is characterized by a lack of published exposure criteria. Early Russian workers[17,23] proposed an overall limit to ultrasonic exposure of 100 dB, regardless of frequency. This was probably a cautious move made in the absence of data to quantify some of the physiological effects being reported at that time. Only two frequency dependant criteria are known. The first was due to Grigor'eva[2] and is shown in Fig. 5. The levels at and below a frequency of 16 kHz are based on the experimental results of temporary threshold shift measurements, and at 20 kHz and above as a result of experiments to detect physiological changes.

However, later in the same year (1966), Grigor'eva[22] proposed a level of 110 dB in the 20–100 kHz frequency range, and mentioned that this had been incorporated into a (USSR) Ministry of Health memorandum.

The criterion due to Acton,[1] also shown in Fig. 5, was based on experimental evidence to prevent both auditory and subjective effects in the greater part of population exposed over a working day. The author did not feel justified in extrapolating this criterion beyond the one-third-octave band centred on 31.5 kHz on the basis of available experimental evidence.

Conclusion

Many of the reports of effects due to exposure to ultrasound must be regarded as anecdotal rather than factual. Further confusion has undoubtedly arisen because results obtained with small,fur-covered animals have been transposed directly to man, and because airborne exposure has not been sufficiently differentiated from liquid or solid-coupled exposure. Nevertheless, there is ample evidence to show that exposure to high levels of ultrasound can have some effects on man.

In industry the exposure to the high levels of high-frequency audible sound which accompanies many ultrasonic processes is more likely to prove troublesome than the ultrasonic frequencies themselves. Subjective effects include headaches, nausea, tinnitus, possibly fatigue and so on, and some temporary threshold shifts in the hearing have been observed as a result of experimental laboratory exposures to ultrasound.

Two, not dissimilar, exposure criteria have been published, both in the 1960s.

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