HSE
Health & Safety Executive

Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency

Prepared by the
Institute of Sound and Vibration Research
for the Health and Safety Executive

CONTRACT RESEARCH REPORT

343/2001

Damage to human hearing by airborne sound of very high frequency or ultrasonic frequency

B W Lawton
Research Fellow
Institute of Sound and Vibration Research
University of Southampton
Highfield
Southampton
SO17 1BJ
United Kingdom

This literature review examines the audiological, occupational hygiene and industrial safety literature on the subjective and auditory effects of audible sound in the very high frequency range (10-20 kHz) and also in the inaudible ultrasonic range (greater than 20 kHz, generally thought to be the upper frequency limit of young normal hearing). Exposure limits have been proposed, with the intent of avoiding any subjective effects and any auditory effects, in any exposed individuals. The evolution of these internationally recognised Damage Risk Criteria and Maximum Permitted Levels has been examined critically. Conclusions and recommendations are offered in respect of hearing damage and adverse subjective effects caused by sounds outside the customary frequency range for occupational noise exposure assessments.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the author alone and do not necessarily reflect HSE policy.

HSE BOOKS

First published 2001

ISBN 0 7176 2019 0

SUMMARY

A number of Damage Risk Criteria and Maximum Permissible Levels were first recommended by individual researchers in the 1960s. These tentative recommendations, supported by limited experimental and survey data, were then taken up by national and international bodies.

For the very high frequencies, 10-20 kHz, the limits were given as one-third-octave band Sound Pressure Levels in the range 75-85 dB, to avoid unpleasant subjective effects in exposed persons; higher noise levels were found to cause annoyance, tinnitus, headaches, fatigue and even nausea.

For ultrasonic components above 20 kHz, the limits were set to avoid hearing damage in the audible (lower) frequencies. One-third-octave band levels of 105-115 dB were observed to produce no temporary hearing loss, and were therefore judged non-hazardous in respect of permanent hearing damage.

Since the introduction of these recommended limits, there have been no reports showing systematic hearing loss trends associated with occupational exposure to very high frequency noise. Review of the scant literature shows few workers represented, and none with more than about five years daily contact with potentially harmful noise. Workday exposure conditions are not described sufficiently to judge if any recognised limit had been exceeded. The reported hearing deficits were unconnected to exposure duration (in years), and were more dominated by age than by noise. Moreover, conventional wideband noise, of such a level and duration as to be recognised as an “ordinary” occupational hazard, can cause hearing loss in the very high frequency range. In addition to the noise-sensitive frequencies 3, 4 and/or 6 kHz., there may be a second region of susceptible frequencies over the range 12-16 kHz. To aid identification of possible noise-induced hearing damage in the 12-16 kHz region, preliminary data are presented showing the expected threshold shift due to natural ageing.

None of the recommended limits have a fully-developed Exposure Level, combining noise level and duration on a daily basis. Where duration is considered at all, there is an equal-energy trading relationship: halving of noise duration allows a 3 dB increase in level. However, the recommended limits have two stated aims: to avoid subjective effects and to avoid hearing damage. In sensitive individuals, adverse subjective effects might be expected to appear shortly after the start of a very high frequency noise exposure. An increase of permitted band level, in line with any duration correction, would hasten the onset of subjective effects in sensitive individuals, and probably involve a larger proportion of the exposed population. Both of these outcomes are undesirable: a relaxation of maximum acceptable level, to account for reduced daily duration, works to thwart one stated aim of any recommended limit.

After consideration of the relevant literature on subjective and auditory effects, there seems to have been no significant progress since Damage Risk Criteria and Maximum Permissible Levels were first proposed in the 1960s. As a first step forward, a structured survey of subjective effects, linked to measured band levels, would confirm (or otherwise) the long-established limits for unprotected ears, and establish the prevalence of adverse subjective effects. A dose-response relation might follow.

It is too early to think of a dose-response relation for hearing injury. A census is needed to determine how many ultrasonic tools are in use throughout UK industry, and how many workers are exposed to potentially harmful acoustic output from these devices? Once the population at risk has been quantified, paths for future research may be opened.

CONTENTS

1. INTRODUCTION

During the late 1960s, hearing Damage Risk Criteria were proposed for noise exposures involving very high frequencies (10-20 kilohertz) and extending into the ultrasonic frequency range (greater than 20 kHz, usually thought to be the upper frequency limit of young normal hearing). These DRCs or Maximum Permissible Levels appear to have been put forward without extensive research on dose-response relationships, to control the risk of hearing loss due to occupational noise not adequately quantified by A-weighted Sound Level. It is worthwhile to ask if, during the intervening decades, there has been sufficient advancement in this topic to allow improvement of, or at least confirmation, of the existing MPLs.

1.1 AIMS

This document is a review examining the relevant literature from the 1960s to the present day. Searches were made of the acoustical, medical, occupational hygiene and industrial safety literature, seeking information on hearing damage or dysfunction, and subjective reaction caused by airborne sound with components outside the customary frequency range for assessment of occupational noise. Research reports, case studies and Damage Risk Criteria have been critically reviewed and assessed, with summary conclusions offered in respect of both subjective and auditory effects which might be expected from very high frequency noise.

At the outset of this work, a number of questions were posed:

- What Damage Risk Criteria or Maximum Permissible Levels are there which deal specifically with noise of very high frequency or ultrasonic frequency?
- How do these limits compare, in terms of maximum permissible level and duration?
- Do the various DRCs indicate a degree of intended protection, that is, what percentage of the exposed population is protected against what hearing loss "low fence"?
- Has hearing injury been associated with work situations where a DRC or MPL has been exceeded?
- Has hearing injury been suggested by case studies of single individuals, or investigated more-or-less systematically by survey? Were acoustic conditions reported adequately?
- Is sufficient information available to indicate the prevalence / incidence of hearing injury?
- What is the nature of the suspected / reported auditory dysfunction, e.g. temporary threshold shift, permanent hearing loss, or tinnitus?
- In what frequency range is the effect manifest in human hearing: in the conventional audiometric range up to 8 kHz, or the very high frequencies 10-20 kHz?
- Can hearing loss, either noise-induced or age-associated, be reliably measured in the frequencies beyond the audiometric range?
- Are there recognised clinical features which would support a diagnosis of very-high-frequency noise-induced hearing loss?

- Is there sufficient data available to postulate a dose-response relation, which would be necessary to establish an authoritative noise Exposure Limit?

Answers to these questions will set out the present state of knowledge; negative answers may point to the need for further work.

1.2 ORGANISATION AND METHOD

The contents of this report are drawn exclusively from critical reading of the works listed in the references, although not all have been reviewed. Only English-language sources were consulted. This restriction is not as serious as it might seem. Important authors, notably German and Scandinavian, frequently publish in English to reach an international audience. Russian work is often summarised in abstracting journals. Useful concepts quickly appear in English, as researchers or administrators try to apply published results.

In dealing with any particular topic, a standard approach has been adopted. A brief introduction is put forward, stating the problem as this reviewer sees it. Individual research papers, conference contributions, government recommendations, etc., are then reviewed in chronological order, with an attempt made to capture the essence of each. After all the reviews have been presented, the present state of knowledge is summarised.

Inevitably in works of this sort, a number of technical terms must be used. These terms, which are required for technical accuracy, quickly become tedious in their full enunciation. The same may be said for the names of various organisations. Therefore, a number of abbreviations will be employed throughout this review, as given here.

ACGIH	—	American Conference of Governmental Industrial Hygienists
BS	—	British Standard
BSI	—	British Standards Institution
dB	—	decibel (re 20 micropascal)
dB(A)	—	decibel, unit of A-weighted Sound Level
DRC	—	Damage Risk Criterion
EN	—	European standard or ‘Euronorm’
IEC	—	International Electrotechnical Commission
IRPA	—	International Radiation Protection Association
ISO	—	International Organization for Standardization
kHz	—	kilohertz, frequency in thousands of hertz
$L_{\mathrm{Aeq,8h}}$	—	A-weighted equivalent continuous Sound Level, over 8 hours
MPL	—	Maximum Permissible Level
NIHL	—	noise-induced hearing loss
SPL	—	Sound Pressure Level
TTS	—	temporary threshold shift
VHF	—	very high frequency, tones or bands of noise in the range 10-20 kHz
WHO	—	World Health Organization

2. EXPOSURE LIMITS

2.1 STATEMENT OF LIMITS FROM AROUND THE WORLD

There are a number of ultrasound DRCs first recommended by research organisations and individuals, and later adopted by governmental bodies and by international organisations. These limits are given in Tables 1 and 2, respectively. The left-hand column of each table indicates the source of each recommendation; the remaining columns list Maximum Permissible Levels as one-third-octave band SPLs. Any noise with a component exceeding one or more of the band limits would be deemed hazardous.

It seems that Soviet, UK and American reports from the 1960s set the scene with a reasoned approach, supported by limited experimental and survey data. These tentative first limits were then taken up by national and international bodies, and repeated with enough regularity to gain a degree of authority, perhaps not deserved.

Grigor'eva (1966)

The extensive use of ultrasonic machinery in Soviet industry raised the question of harmful effects of air-borne ultrasound. Experiments were conducted at the All-Union Central Scientific Research Institute of Occupational Hygiene in Moscow to contrast the physiological effects of tones in the ultrasonic and audible regions.

An unspecified number of subjects were exposed for an hour to a tone of 20 kHz at 110 dB. Tests were made to examine shift of hearing threshold over the frequency range 250 Hz to 10 kHz. Pulse rate, body temperature and skin temperature were also monitored. These tests showed no appreciable effect, even when the SPL was increased to 115 dB. These same subjects were given a one hour exposure to a 5 kHz tone at 90 dB: a considerable TTS was found. The 5 kHz tone at 110 dB produced a powerful vascular response.

These results indicated that air-borne ultrasound is considerably less hazardous than audible sound. A limit of 120 dB was proposed for airborne ultrasound (presumably 20 kHz or greater). Further TTS experiments were performed to determine acceptable Sound Pressure Levels for high-frequency tones in the audible region. From these further results, Grigor'eva suggested the following limits, without reference to the duration of the sound:

One-third-octave band centre frequency (kHz)	6.3	8	10	12.5	16
Sound Pressure Level (dB)	75	80	85	90	90

These band limits are intended to avoid the possibility of temporary threshold shift, presumably to take advantage of an underlying concept: A sound which does not produce temporary dullness of hearing cannot produce a permanent noise-induced hearing loss.

Acton (1968)

During the 1960s, Acton was exploring the possibility of hearing damage by the noise of industrial ultrasonic equipment. He accumulated a number of spectra from industrial tools and

Table 1
Maximum Permissible Levels for airborne ultrasound, recommended by research groups or individuals

One-third-octave band centre frequency (kHz)	8	10	12.5	16	20	25	31.5	40	50	Wide-band 10 kHz –
Source:										
Grigor'eva (1966)	80	85	90	90	–	–	–	–	–	120
Acton (1968)	75	75	75	75	110	110	110	–	–	
Parrack, 1969 cited in WHO (1982) and Acton (1983)	–	80	80	80	105	110	115	115	115	
Acton (1975, 1976)	75	75	75	75	75	110	110	110	–	
Acton, Hill (1977)	–	75	75	75	75	110	110	110	–	

Table 2
Maximum Permissible Levels for airborne ultrasound, set out by organisations or national governments

One-third-octave band centre frequency (kHz)	8	10	12.5	16	20	25	31.5	40	50
Source:									
Internat. Lab. Off. (1977)	–	–	75	85	110	110	110	110	110
ACGIH, 1979 cited in Lee (1980)		80	80	80	105	110	115	115	115
WHO (1982)									
Japan	90	90	90	90	110	110	110	110	110
USSR	–	–	75	85	110	110	110	110	110
US Air Force	–	–	85	85	85	85	85	85	–
Canada	80	80	80	80	80	110	110	110	110
Sweden	–	–	–	–	105	110	115	115	115
INRC/IRPA (1984)									
occupational exposure	–	–	–	–	75	110	110	110	110
general public	–	–	–	–	70	100	100	100	100
Health Canada (1991)	–	–	–	75	75	110	110	110	110
ACGIH (1998) ceiling values	–	105	105	105	105	140	145	145	145

appliances showing ultrasonic components in their one-third-octave analyses, along with reports of (or absence of) subjective effects experienced by the users. In addition, several young normally-hearing subjects were exposed to ultrasonic tones from a tuneable Galton whistle.

Maximum Permissible Levels were proposed on the basis of possible hearing damage risk, and the presence or absence of subjective effects for measured spectra. If band levels were below 75 dB for the one-third-octave bands centred at 8, 10, 12 and 16 kHz, then no subjective effects would be expected. Symptoms including nausea, fullness in the ears, tinnitus and persistent headaches would be avoided. A tentative extrapolation of DRCs (current at the time) suggested that 8 hour exposures to levels of 110 dB in the 20 kHz, 25 kHz and 31.5 kHz bands would not result in hearing loss in the audible frequencies.

This work by Acton gives a clear statement of the dual-aim limit in the English-language literature. Russian work at the time showed the possibility of auditory harm from possibly inaudible ultrasonic noise. Audible but VHF sounds were found to produce unpleasant, even alarming, subjective effects. To prevent both insult and injury, different levels need to be applied to sounds in the two frequency regimes.

Acton (1975)

In the intervening few years since Acton's first proposal of 1968, a shortcoming of the criterion came to light, concerning the limit value for one particular frequency band. The original proposal set a limit of 110 dB for the one-third-octave band centred at 20 kHz, with nominal band-edge frequencies of 17.6 and 22.5 kHz. The lower end of this frequency range is within the audible range for a significant proportion of the population, notably young females. At levels of 110 dB, such VHF sounds would be expected to cause severe subjective effects. Therefore, Acton revised his limiting criterion downward to 75 dB for the 20 kHz one-third-octave band.

The revised criterion was summarised as seen below, in terms of maximum levels in frequency bands:

75 dB	octave band centred on 16 kHz, or one-third-octave bands centred on frequencies up to and including 20 kHz, or narrow bands centred on frequencies up to 22.5 kHz
110 dB	octave bands centred on 32 kHz and higher, or one-third-octave bands centred on frequencies of 25 kHz and above, or narrow bands centred on frequencies of 22.5 kHz or higher

Note: This same revised criterion may be found in Acton (1976), and in Acton and Hill (1977).

The careful reader will note that these limits will work only for simple sounds comprising a fundamental with harmonics: each component would fall in a different band, no matter which bandwidth was chosen (octave, third-octave, or narrow band). However, for broadband noises, each of three one-third-octave band levels might be less than the limit value, but add to give an octave level greater than the limit. A numerical example will illustrate the point: one-third-octave levels of 74, 74 and 74 dB add to give an octave level of 78.8 dB. Similar ambiguity might occur in the case of two or more fundamental tones, each with harmonics, and the possible complication of sum and difference tones. Careful consideration must be given to cases where the criterion is capable of conflicting pass-fail results.

International Labour Office (1977)

This labour organisation recommended that maximum Sound Pressure Levels near workplace sources of ultrasound should not exceed 75 dB in the one-third-octave band centred at 12.5 kHz, 85 dB in the 16 kHz band, and 110 dB for the bands at 20 kHz and higher. For any total duration of ultrasound not exceeding 4 hours, these levels might be relaxed as follows:

duration 1 to 4 hours	6 dB permitted increase
15 minutes to 1 hour	12 dB
5 to 15 minutes	18 dB
1 to 5 minutes	24 dB

These supplements for reduced time are intended to represent the "equal energy hypothesis": two sounds with identical amounts of acoustic energy represent the same risk to hearing. For a constant degree of risk, halving or doubling the duration of any sound should be countered by a change of level, +3 dB or -3 dB respectively, for constant acoustic energy. The supplements from the ILO do not follow the equal energy line exactly, but sawtooth about it, sometimes more lenient, sometimes harsher.

Almost as a footnote, a valuable insight is offered concerning the occupational environment. In practice, the audible high frequencies which frequently accompany ultrasound are sufficient to cause the effects attributed to ultrasound. Such VHF noise, in the range 10 to 20 kHz, may be a problem for some individuals, particularly for younger persons, while these components may not be audible to the (older) supervisors who have the authority and responsibility for its control.

International Non-Ionizing Radiation Committee (1984)

Band limits for occupational exposure to VHF sound and airborne ultrasound may be seen in Table 2; these limits apply to continuous exposure of workers for an 8 hour working day. For shorter durations, the permissible levels may be increased:

duration 2 to 4 hours	3 dB permitted increase
1 to 2 hours	+6 dB
less than 1 hour	+9 dB

As seen in the previous review, these supplements for reduced time are intended to represent the "equal energy hypothesis", with a halving or doubling the duration of any sound opposed by a change of level, +3 dB or -3 dB respectively, for constant acoustic energy. These supplements from the INRC do not follow the equal energy line exactly but sawtooth below it: the supplements are conservative.

Damongeot, André (1985)

A number of daily MPLs are presented for what the authors term "low frequency ultrasound", ranging from 16 kHz to 100 kHz. These limits from the world literature are reproduced here in Table 3: some have been seen before, others are new to this document. Part a of the Table gives band limits from various sources; there is fair agreement of the limits, save for the 20 kHz one-third-octave band. Part b indicates permitted relaxations of quoted limits for shorter exposure time (shorter than an notional 'exposure day' of 4 to 8 hours); the trading relation between level and duration is 3 dB per halving or doubling of duration.

Table 3
Limits for airborne ultrasound
Part a. Limits for whole-day exposure

One-third-octave band centre frequency (kHz)	10	12.5	16	20	25	31.5	40	50	63	80	100
Source:	band level (dB)										
IRPA (1984)	—	—	—	75	110	110	110	110	110	110	110
Australia , 1981	75	75	75	110	110	110	110	110	—	—	—
USA, 1981	80	80	80	105	110	115	115	115	—	—	—
Canada, 1980	80	80	80	110	110	110	110	110	—	—	—
Sweden, 1978	—	—	—	105	110	115	115	115	115	115	115
USSR, 1975	—	75	85	110	110	110	110	110	110	110	110
Norway, 1978	–	–	–	–	—— 120 (octave) ——			—— 120 (octave) ——			–

Part b. Supplement for durations less than 8 hours

Source:	Duration (hours)	Correction (dB)
IRPA (1984)	2 - 4	+3
	1 - 2	+6
	< 1	+9
Sweden, 1978	1 - 4	+3
	< 1	+9
USSR, 1975	1 - 4	+6
	¼ - 1	+12
	< ¼	+18

These authors comment that most situations involving ultrasound should be approached as an ‘audible noise problem’, requiring measurement of the L_{Aeq} up to 20 kHz, combined with an ‘ultrasound problem’, necessitating one-third-octave band measurements upward from the high-frequency audible range 8 or 10 kHz. This advice was confirmed in a 1988 report by these same investigators. Fifty-six ultrasonic welders were surveyed, to determine both the broadband audible noise and the ultrasonic components from each. The operators’ exposures were categorised using $L_{Aeq,8h}$ for the audible spectrum:

“safe”	$L_{Aeq,8h} < 85$ dB(A)
“presumption of danger”	85 dB(A) $\leq L_{Aeq,8h} < 90$ dB(A)
“danger”	$L_{Aeq,8h} \geq 90$ dB(A)

A similar categorization was made using the range of ultrasound level and time limits given in Table 3. Any ultrasonic output less than the lowest limit for any frequency band was judged “safe”. An output greater than any highest limit was put in the “danger” category. The “presumption of danger” band fell between the lowest and highest limit values for any frequency. Only 1 of the 56 welders was judged “safe” by both the conventional $L_{Aeq,8h}$ noise-at-work criteria and the range of ultrasonic limits.

Health Canada (1991)

This Canadian government document presents a review of the health effects expected from occupational exposure to ultrasound. With high-power industrial tools or appliances, the objective is to expose the workpiece to vibratory energy of sufficient magnitude to bring about permanent physical change in the material; an example might be welding. The main hazard to the tool user is energy input to the body by accidental contact with the tool head, or any fluid containing ultrasonic energy. However, many industrial or commercial devices also release airborne energy, giving high Sound Pressure Levels in both the audible and ultrasonic frequency ranges. This incidental sound can produce both physiological and hearing effects.

For airborne ultrasound at levels greater than approximately 155 dB, acute harmful effects will occur in exposed persons, primarily as a result of sound absorption and subsequent heating. It was deemed plausible that lengthy exposure to such high levels might raise body temperature to mild fever levels during the exposure periods. However, such high Sound Pressure Levels had never been encountered in either commercial or industrial applications.

Reports of subjective and auditory effects of lower levels of airborne ultrasound were briefly reviewed. These comments need not be considered here; the source documents are scrutinised in detail elsewhere in the present report.

Maximum Permissible Levels were set out for airborne ultrasound. For the one-third-octave bands centred at 16 and 20 kHz, the limit was set at 75 dB; for the bands at 25 to 50 kHz, the limit was 110 dB. These band limits are independent of duration as subjective effects may occur immediately.

AGCIH (1998)

In referring to Table 2, one may see that the American industrial hygiene limits for ultrasound are somewhat more lenient than limits from other nations or bodies. These more permissive Threshold Limit Values are said to “represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech.” The implication is that such high levels, for hours per day over many working years, would not produce socially-significant hearing loss over the frequencies 0.5 to 4 kHz, generally considered to carry the majority of speech information.

A line of reasoning is offered: previous ACGIH limits for the frequencies 10 to 20 kHz were set to prevent subjective effects. "Subjective annoyance and discomfort may occur in some individuals at levels between 75 and 105 dB for the frequencies from 10 kHz to 20 kHz especially if they are tonal in nature. Hearing protection or engineering controls may be needed to prevent subjective effects." It appears that the American Conference of Governmental Industrial Hygienists is willing to accept some degree of subjective effects in a fraction of the exposed individuals.

For the frequency bands 25 kHz and higher, the source document gives band levels of 110 and 115 dB, with the ultrasound measured in air and the receiver's the head also in air. However, these Threshold Limit Values assume that the human body is coupled to the source by water or some other substrate. "The threshold may be raised by 30 dB when there is no possibility that the ultrasound can couple with the body by touching water or some other medium." In accordance with the present interest in airborne ultrasound, the higher values are reported in Table 1. This reviewer suspects that these high values, 140-145 dB, are linked to the report of Parrack (1966): ultrasonic tones at slightly higher levels were shown to produce TTS which recovered within a relatively short time post-exposure. The ACGIH limit values seem intended to avoid TTS which, if repeated on a regular basis, might be expected to develop into a permanent NIHL.

The striking difference between the ACGIH limits and all others suggests some fundamental difference in attitude. This reviewer believes that the ACGIH has pushed its acceptable exposure limits to the very edge of potentially injurious exposure.

Note: The ACGIH document mentions the possible need for hearing protection. Although attenuation for protective equipment is not usually specified beyond 8 kHz by the makers, such data does exist. See reports by Townsend, Bess (1973); Berger (1983, 1984); Behar, Crabtree (1997); Crabtree, Behar (2000). Good quality plugs or muffs generally have a mean attenuation in the range 20-40 dB over the frequency range 8-18 kHz when tested by the threshold shift technique; greater attenuation can sometimes be achieved when an acoustic test fixture is used.

2.2 INTERPRETATION OF EXISTING OR PROPOSED BAND LIMITS

Considering the audible frequencies, up to and including the 16 kHz band, it may be seen that the proposed limits of Tables 1 and 2 cover a relatively narrow range (ignoring the extreme values of the ACGIH). Values of 80 dB are typically recommended to avoid unpleasant subjective effects. It is instructive to compare this typical level with known diffuse-field thresholds for such sounds heard by normal listeners aged 18-25; see Table 4. The right-hand column of the Table gives the difference, limit minus threshold as a form of Sensation Level in dB. For young persons, unpleasant subjective effects would be expected for sounds of relatively modest Sensation Levels. For older persons, with a degree of age-associated hearing deterioration in these high frequencies, the typical limit value of 80 dB would seem somewhat quieter, possibly even inaudible.

It is also worthwhile to consider if the conventional ultrasonic frequencies, 20 kHz and higher, are audible to the human ear. Work by Takeda *et al.* (1992) suggests that most adults will not perceive sound of frequency greater than 16 kHz; see Table 5. This is a strange idea, having

Table 4
Typical band limits for high-frequency sounds, in terms of Sensation Level, that is, dB above threshold from BS EN ISO 398-7: 1998

Frequency (kHz)	Typical band limits (dB)	Threshold, diffuse-field (dB)	Limit in Sensation Level (dB)
8	80	5.5	74.5
10	80	9.5	70.5
12.5	80	13.0	67.0
14	(80)	21.0	59.0
16	80	47.0	33.0

Table 5
Values of the upper frequency limit of hearing by percentile, for otologically normal subjects in age bands of 10 years, from Takeda *et al.* (1992)

Percentile	10%	25%	50%	75%	90%
Age (years)	Frequency (kHz)				
20-29	18.0	17.1	15.9	14.9	13.8
30-39	16.6	15.2	14.5	13.6	12.4
40-49	14.6	13.8	12.9	11.8	10.6
50-59	13.2	12.2	11.0	9.6	8.2
60-69	11.2	9.9	8.3	5.3	1.8

noise level limits for sounds which may not even be audible. The suggestion is that one's hearing may be at risk from sound which cannot be heard. This idea will be pursued in a later section dealing with threshold shift, both temporary and permanent.

2.3 A SINGLE NUMBER APPROACH

There is an attractive simplicity to the idea of a single number which describes the magnitude of any sound. In the field of noise in the workplace, hearing damage potential is conventionally measured in terms of daily personal noise exposure level ($L_{EP,d}$), which combines Sound Pressure Level, the frequency response of the ear (by means of the A-weighting), and noise duration normalised to a notional 8 hour workday. For a worker without hearing protection, an $L_{EP,d}$ of 95 dB would be recognised as a danger to the hearing. An $L_{EP,d}$ of 80 dB might be judged loud or unpleasant, but such an exposure would not be deemed a hearing hazard. In contrast to the one-third-octave band limits seen above, a single number scheme might be more useful (certainly more convenient) for workplace tools or appliances producing ultrasonic as well as audible noise.

Körpert, Vanek (1987)

A number of rating criteria exist to assess the hazard of airborne ultrasound. These authors present arguments against the criteria of Acton (1968, 1975, 1983) and in favour of the single number rating of AU-weighted Sound Level. The AU weighting is discussed below, in the review of the standard BS EN 61012:1998.

The various Acton criteria are criticised on a number of points, with reference to measured spectra from ultrasonic devices making discrete tones or continuous noise:

- The 75 dB limit value for frequencies falling within the 16 kHz octave band is intended to minimise subjective effects. For frequencies falling within the 32 kHz octave, the limit of 110 dB is aimed at preventing hearing damage.
- The boundary between the subjective and hearing limits is uncertain. Depending upon the actual frequencies of individual spectral components, ultrasonic devices with very similar spectra might be assessed against different limit values.
- The Acton criteria are useful only for spectra with discrete tones; wide-band noise cannot be assessed.

Each of these shortcomings is overcome if ultrasonic noise is quantified in terms of Sound Level with a combined AU frequency weighting. The long-established A-weighting takes account of the hearing hazard of components within the conventional audible range, including sub-harmonics of any ultrasonic tones. The U-weighting (see BS EN 61012:1998) is a low-pass filter, intended to eliminate both tones and continuous spectra in the ultrasonic region. Finally, the U response is said to account for the loudness (and thus the hazard potential) of ultrasonic components of any noise. It is plain that these authors strongly favour AU-weighted Sound Level. They propose a limit Sound Level value of 85 dB(AU) to avoid noise-induced hearing loss; duration of exposure is not considered.

Any use of the AU-weighting seems to oppose the intentions of the DRCs and MPLs seen above. Consider the following situations. A VHF tone of 16 kHz at 95 dB SPL would be considered too high in relation to most of the limits of Tables 1 and 2; subjective reactions would be expected. That same tone would be measured as 75 dB(AU) and thus deemed acceptable. Likewise, an ultrasonic tone of 31.5 kHz at 140 dB SPL would be judged dangerously high according to virtually all of the limits of Tables 1 and 2, and capable of producing hearing threshold shift. However, a measured value of 75 dB(AU) would again be judged acceptable (without risk of hearing damage). The AU-weighting seems likely to hide from view any VHF components. In addition, the AU-weighting seems intended to eliminate ultrasonic components from consideration, rather than assess such noises fairly according to widely-accepted guidelines.

BS EN 61012:1998

The frequency weighting characteristics of Sound Level Meters, as described in British and IEC standards, are not specified above 20 kHz. Consequently, some instruments may not respond to the ultrasonic airborne energy emitted, for example, by cleaners, mechanical tools and welders which operate above this frequency. Moreover, other meters may be unsuitable for measuring the audio-frequency part of the sound emitted by such equipment; the ultrasound will give rise to inflated readings if the frequency response of a particular Sound Level Meter happens to extend to the operating frequency of the tool or device being surveyed.

With ultrasonic equipment, the noise of interest arises from audible sounds produced by the (inaudible) ultrasonic process. One practice is to use the A-weighting response in conjunction with a low-pass filter having a very sharp cut-off above 20 kHz. As seen above in the comments regarding Körpert and Vanek (1987), such a practice can be misleading: potentially hazardous sounds may be judged harmless.

The purpose of this British Standard (and its international predecessor IEC 61012:1990) is to specify the relative response of such a low-pass filter; termed the U-weighting as given in Table 6. The A-weighting is also given. When the U- and A-weightings are used together, the resultant AU-weighting is simply the sum of the two individual responses.

2.4 CONCLUSIONS ON LIMITS

In the Introduction, a number of questions were set out for consideration. Several have been answered in this Chapter.

- What Damage Risk Criteria or Maximum Permissible Levels are there which deal specifically with noise of very high frequency or ultrasonic frequency?

- How do these limits compare, in terms of maximum permissible level and duration?

From the evolution of MPLs as seen here, it is plain that the limiting level for the very high frequencies, up to 20 kHz, was set to avoid unpleasant subjective effects. The actual level was set low, at 75-85 dB, to avoid effects in young workers, usually female. For older workers, age-associated hearing loss (to be examined in detail later) would make 75-85 dB range at quite a low loudness, if audible at all. For ultrasonic components, MPLs in the range 105-115 dB were established to avoid the possibility of hearing damage in the much lower audible frequencies. The relative homogeneity of the limits, based on really quite limited experimental information, suggests reluctance of any government or body step out of line with what has been said before. Save for the ACGIH limits. The American limits are noticeably more lenient, with higher recommended levels at all frequencies. These higher levels indicate an acceptance that

Table 6
Frequency responses of the U, A and AU weightings

One-third-octave band centre frequency (Hz)	Relative frequency response (dB) U-weighting*	A-weighting	AU-weighting
20	0	-50.5	-50.5
25	0	-44.7	-44.7
31.5	0	-39.4	-39.4
40	0	-34.6	-34.6
50	0	-30.2	-30.2
63	0	-26.2	-26.2
80	0	-22.5	-22.5
100	0	-19.1	-19.1
125	0	-16.1	-16.1
160	0	-13.4	-13.4
200	0	-10.9	-10.9
250	0	-8.6	-8.6
315	0	-6.6	-6.6
400	0	-4.8	-4.8
500	0	-3.2	-3.2
630	0	-1.9	-1.9
800	0	-0.8	-0.8
1.00 k	0	0	0
1.25 k	0	+0.6	+0.6
1.60 k	0	+1.0	+1.0
2.00 k	0	+1.2	+1.2
2.50 k	0	+1.3	+1.3
3.15 k	0	+1.2	+1.2
4.00 k	0	+1.0	+1.0
5.00 k	0	+0.5	+0.5
6.30 k	0	-0.1	-0.1
8.00 k	0	-1.1	-1.1
10.00 k	0	-2.5	-2.5
12.50 k	-2.8	-4.3	-7.1
16.00 k	-13.0	-6.6	-19.6
20.00 k	-25.3	-9.3	-34.6
25.00 k	-37.6		-50.0*
31.50 k	-49.7		-65.4*
40.00 k	-61.8		-81.1*

* specified in BS EN 61012:1998

subjective effects are not harmful, and will not produce any decrement in communication ability. The higher acceptable levels may also be linked to the American view (which may or may not be held currently) that some degree of hearing loss is acceptable in a working population.

There is also a range of view on the influence of time, as it is related to exposure dose. None of the DRCs seen here have a fully-developed Exposure Level, calculated from the variables SPL and noise duration. Where duration is considered at all, there is a trading relationship broadly in line with equal-energy considerations: halving of noise duration allows a 3 dB increase in level. This alteration of limit, to account for duration, is a basic feature of schemes to assess the hearing damage potential of any occupational noise. However, the band limits set out by researchers and governmental bodies have two stated aims: to avoid subjective effects and to avoid hearing loss, either temporary or permanent. In sensitive individual workers, unpleasant subjective effects might be expected to appear almost as soon as an ultrasonic noise exposure begins. An increase of permitted band level, in line with a daily duration correction, may be expected to hasten the onset of adverse subjective effects in sensitive individuals, and possibly to involve a larger proportion of the exposed population. Any duration supplement works to thwart one stated aim of the limit.

- Do the various DRCs indicate a degree of intended protection, that is, what percent of the exposed population is protected against what hearing loss "low fence"?

On this point, all of the limits reviewed here are quite plain: the Maximum Permissible Levels are set to avoid *any* subjective effects and *any* auditory effects.

When considering hearing damage by noise, the concept of intended protection is quite sophisticated, requiring knowledge of the noise dose (level and duration) required to produce a hearing damage response over the range of susceptible individuals. With knowledge of how all of the various factors interact, one may predict what proportion of an exposed population would suffer a specified degree of hearing loss from a known exposure. For conventional broadband occupational noise as might be experienced in any number of workplaces, the idea of intended protection may be applied, as long as one is prepared to grapple with the troublesome social concept of the "low fence" which defines the boundary between acceptable and unacceptable noise-induced hearing loss. As far as sound of very high frequency or ultrasonic frequency is concerned, the dose-response relation is unknown: the limiting levels have been deliberately set low to avoid any response whatever.

3. SUBJECTIVE AND AUDITORY EFFECTS

As reported in the previous Chapter, the recommended maximum limits for sounds with frequency components greater than 8 kHz are built upon two foundation stones. Very high frequency sounds are capable of causing unpleasant subjective effects at modest levels; ultrasonic sounds are capable of causing damage to the hearing at high levels. Such acoustic insult and acoustic injury should not be part of the working environment, therefore levels were set to avoid the possibility of either. This Chapter will outline the scanty research upon which the MPLs rely. Subsequent research will also be considered.

3.1 SUBJECTIVE EFFECTS

In 1953, Chadwick wrote, as a Royal Air Force medical officer, of the effects of jet noise heard without protection, very close to the engine: "The advent of the turbo-jet engine focused attention on certain subjective sensations which occurred infrequently and erratically. Many injudicious Press reports have appeared from time to time based upon scanty knowledge of possible harmful effects resulting from ultrasonic frequencies generated by jet aircraft. This no doubt makes sensational reading, but it has lead to a number of purely psychological disturbances being experienced, not only by jet personnel but by other people not even remotely connected with the jet engine. A transient vestibular irritation induced by standing in close proximity to turbo-jet engines when run at certain speeds has been experienced by many observers. It is unlikely that this phenomenon is due to the presence of ultrasonic waves as was first suggested. It is well known that stimulation of the vestibule can be caused by sufficiently loud acoustic stimuli."

In the early 1950s, apparently no great risk was attached to standing within 2 metres of the intake of a jet engine, where one might experience SPLs over 140 dB, leading to general instability, weakness and even nausea. Chadwick concluded: "At the moment, we have no grounds to suppose ultrasonic frequencies are mainly responsible for these symptoms. The effects are largely due to high intensities and not to high frequencies as such."

Similar views were current in the United States at about this time. In 1966, Parrack gave a substantial summary of what was then known about the effect of airborne ultrasound on humans. After the Second World War, jet engines came into widespread use for aircraft propulsion, with the result that military personnel were subject to extremely high noise levels; there was uncertainty and apprehension amongst ground- and aircrew regarding the effect of such noise. The term "ultrasonic sickness" appeared in the popular press, to denote nausea, vomiting, excessive fatigue, and disturbance of muscular co-ordination associated with exposure to jet aircraft noise. This journalistic term seems to have remained in the general consciousness long after acoustic analyses of jet engine noise showed the ultrasonic frequencies to be less powerful than components below 1 kHz.

The following reviews will pursue noise-induced subjective annoyance and discomfort, nausea, fullness in the ears, tinnitus and persistent headaches.

3.1.1 Reports Which May Have Influenced DRCs

Skillern (1965)

Measurements were made of the high-frequency noise emitted by industrial ultrasonic devices: two drills, a welder and nine cleaners. These devices had operating frequencies ranging from 15 to 80 kHz, with powers ranging from a few hundred milliwatts to 5 kilowatts. The operators of these appliances gave reports of subjective effects associated with their use.

Reproduced in Table 7 below are the one-third-octave band levels observed at the operator's position, for a selection of the devices tested.

Table 7
Noise levels of several of the ultrasonic devices

One-third octave band centre frequency (kHz)		10	12.5	16	20	25	31.5
Device:	Operating frequency (kHz)	Band level (dB)					
cleaner (no. 4)	20	125	123.5	119.5	133	133.5	110
cleaner (no. 5)	40	77	78	79	96	77	77
cleaner (no. 7)	40	69	75.5	77	92	81	75
cleaner (no. 9)	40	<61	<61	<61	83.5	65.5	<61
cleaner (no. 11)	80	62	69	73	77	73	71
drill (no. 1)	23.1-26.1	91	85	90	81	107.5	84
drill (no. 2)*	23.1-26.1	60	74	60	64	85.5	74

* in acoustic enclosure

The operators were questioned regarding any subjective effects associated with the operation of these devices. In general, the severity of the reported effects was directly related to the magnitude of the band levels.

cleaner (no. 4) Operator didn't use the machine; the noise was too "intense".
Note: The audible high-frequency band levels sum to give 125.5 dB(A); it is little wonder that the operator found the noise of this appliance to be intolerable.

cleaner (no. 5) Headache, malaise, fatigue; when necessary to use device, operator left the room.

cleaner (no. 7) Headache after 15 minutes use.

cleaner (no. 9) No complaints, but tool turned off when not in use.

cleaner (no. 11) No complaints; tool ran continuously.

drill (no. 1) Pain in the ears ("burning sensation in the auditory canal") after a few minutes; headache after 1 hour; nausea after 2 hours.

The author summarized the subjective effects experienced by machine operators: "At 80 dB, individuals expressed no effect, but they chose to turn the instruments off when not in use. At 90 dB, individuals had a feeling of malaise, fatigue, or would leave the location when the ultrasonic instruments were operating."

It is worth noting that the tools found to produce subjective effects all had band levels greater than 75 dB in the VHF audible range. This value figures in a number of proposed limits for ultrasonic noise exposure.

Roscin et al. (1967)

This summary appeared in an abstracting journal:

"The intensity of ultrasound is determined by the working frequency and output of the ultrasonic device, and by the synchronisation of the converter and generator. Protracted exposure to lower-frequency ultrasonic vibrations at levels above 116 dB is harmful to health. On the basis of a comprehensive clinical examination of 300 persons working with ultrasonic instruments, the authors describe the range of symptoms reflecting the effects of high frequency noise and ultrasound. Ultrasound principally affects the vestibular function, whereas high-frequency noise results first and foremost in hearing loss. The authors recommend that ultrasound in the lower frequency range transmitted through air should not exceed a maximum pressure level of 100 dB."

The summary, perhaps a direct translation of the authors' Russian abstract, gives no indication of the frequency ranges defining "high-frequency noise", "lower-frequency ultrasound" or the general term "ultrasound"; interpretation of effects for the stated levels 100 dB and 116 dB depends upon this missing information. However, a survey of 300 ultrasonic workers is too valuable to dismiss out of hand. It seems fair to assume that the authors' intended points were: Airborne sound of frequency in the range 20-50 kHz, and level greater than 116 dB, was found to produce disturbance of balance. Workers' exposure to such frequencies should not exceed a maximum SPL of 100 dB.

Dobroserdov (1967)

This item appeared in the same abstracting journal as the summary for Roscin *et al.* above.

"The author reports the results of studies of persons working with ultrasonic appliances, and of controls not exposed to ultrasound. Auditory sensitivity after exposure to frequencies of 150 000, 14 000, 10 000 and 4 000 c/s, the latent period of visual and oral motor reactions, and vestibular function were examined. It was found that ultrasound waves at a pressure level of 120 dB engender physiological changes and should therefore not be used in industry; on the other hand, ultrasound waves at 100 dB produced no detectable changes in the functions investigated. Exposure to high frequency sound was responsible for much more pronounced hearing loss than was exposure to ultrasound."

Unfortunately, the abstract gives no indication of the boundary between high-frequency and ultrasonic sounds, to specify exactly which sounds "engender physiological changes" in contrast to those "responsible for much more pronounced hearing loss". This potentially useful Soviet research is tantalisingly inaccessible.

Acton, Carson (1967)

This investigation was intended to explore the possibility of hearing damage by the noise of industrial ultrasonic equipment. The appliances in question were drills operating at 20 kHz, small laboratory washers operating at 16 kHz (with an ultrasonic harmonic at 32 kHz), and large washers operating at 20 kHz.

The drills produced maximum one-third-octave band levels in the range 98 to 112 dB at 20 kHz. No complaints were volunteered by the users, all males with some degree of pre-existing hearing loss. The researchers, however, did experience "persistent ringing in the head and an unpleasant 'fullness' of the ears from the noise which was clearly audible yet not very loud".

The small washers had one-third-octave band levels of 91 and 101 dB for the 16 kHz and 31.5 kHz bands respectively. No complaints were received from the female operators. However, the researchers experienced subjective effects from the 16 kHz component, which they described as “a piercing, almost painful, whistle”. The bank of large washers was found to have a rising but indistinct spectrum, increasing from 75 dB for the 6.3 kHz band to 126 dB for the 40 kHz band. The operators, predominantly female, complained of fatigue, tinnitus, nausea and also headaches which persisted for several hours after the noise had ceased.

The authors suggested that the reported subjective effects resulted from audible sound (of frequency less than 20 kHz) at high level. Caution is needed here: the reports of subjective effects come from the authors themselves in two out of three cases.

3.1.2 Later Work

Herman, Powell (1981)

These authors give a review of ultrasound effects and limits; this portion of their work need not be covered here. They do, however, introduce ultrasound sources outside the usual industrial context.

A small survey was made to quantify the acoustic output of intruder alarms found in offices, factories, departmental stores, small shop premises, and a private home. The alarm systems used ultrasonic beams, of frequency 20 to 40 kHz, to detect the presence of an intruder; in most cases, the beam was continuously present, but the alarm mechanism was disabled during normal working hours. Maximum levels were found to be 93, 90.5 and 91.5 dB at 20, 25 and 40 kHz, respectively, at locations were staff or customers might be found. These sounds were reported as being audible to some individuals, and capable of causing headaches amongst staff and extreme annoyance reaction in customers.

An ultrasonic dog repeller was found to have a maximum output of 108 dB, 16 kHz at a distance of 1.5 metres; this level decayed at the expected 6 dB per doubling of distance from the source. The reaction of (human) observers ranged from no perception at any distance, to severe discomfort in the ears about 12.5 metres away, in another room.

Such anecdotes and second-hand reports, although interesting, are of little help.

Holmberg, Landström, Nordström (1995)

Ten subjects were exposed to the noise of an ultrasonic washer and required to rate the annoyance and discomfort it generated. Five men and five women, ranging in age from 23 to 44 years, all with normal hearing thresholds, were given a proof-reading task to do while exposed to 2 minute bursts of the washer noise at varied A-weighted Sound Levels. The ultrasonic washer noise had a wide-band spectrum with maximum levels in the 12.5 kHz and 25 kHz one-third octave bands.

The subjects were asked to rate the amount of “annoyance (mental effect)” and “discomfort (effect located at the ear)” for the washer noise presented at 72, 80 and 96 dB(A). To make the desired rating, each subject marked a seven-point scale, which for annoyance was marked “not at all annoying, hardly at all, rather annoying, quite, very annoying, almost unbearable”; a similar scale was set out for uncomfortable. No significant difference was found between the ratings for annoying and uncomfortable. However, the ratings seemed high to the researchers, prompting them to recommend avoidance of occupational exposures to the noise of this ultrasonic washing appliance above 70 dB(A). This seems a very strong conclusion from a psychological experiment using two-minute noise bursts.

There was, however, another facet to the study: the subjects were asked to adjust the level of a broadband noise (0.3-8 kHz) to match first the annoyance of the ultrasonic washer noise, and then the discomfort caused by the noise. The A-weighted Sound Levels of the adjusted broadband noise did not reproduce the fixed levels of the washer noise, or the intervals between washer noise presentation levels. See the results in Table 8 below.

Table 8
Mean levels of broadband noise adjusted to match the set levels of noise from the ultrasonic washer

Level of ultrasonic washer (dB(A))	Broadband noise level (dB(A)) matched for equal annoyance	matched for equal discomfort
72	65.6	67.0
80	68.0	72.2
96	72.2	76.4

It is obvious that the Sound Level Meter was assessing some noise quantity, as indicated by the relatively large differences in the dB(A) readings. The subjects' chosen A-weighted levels for the broadband noise quality do not mirror these instrumental differences. The Sound Level Meter was sensing some noise components either inaudible to the subjects or inconsequential to their judgements: use of the AU weighting (see BS EN 61012:1998) might have given these researchers a different view of the phenomena under investigation.

3.1.3 Conclusions on Subjective Effects

When occupational exposure to VHF noise and ultrasound was being surveyed in the 1960s, subjective effects were sought. Exposed workers and researchers reported experiencing annoyance, discomfort in the ears, fullness in the ears, malaise, fatigue, nausea, vestibular dysfunction, tinnitus and persistent headaches. Very little work has been done and reported since the 1960s, although it would seem safe to assume that these problems have not gone away in the meantime. A structured survey would be helpful in confirming (or otherwise) the long-established MPLs, and possibly giving information on the prevalence of unpleasant subjective effects at various levels of VHF or ultrasonic noise.

3.2 HEARING LOSS, EITHER TEMPORARY OR PERMANENT

It has long been recognised that high levels of wideband or "ordinary" noise, after sufficient duration, will damage the hearing of exposed individuals. In the occupational sense, the exposure will probably last several hours each workday over a period of years. The principal characteristics of occupational noise-induced hearing loss are:

- It is always sensorineural, affecting the hair cells in the inner ear.
- It is bilateral; the audiometric pattern is similar in each ear.
- The earliest damage is manifest as a threshold shift (a loss of hearing sensitivity) at the audiometric frequencies 3, 4 and/or 6 kHz.

- During stable noise exposure conditions, the hearing losses at 3, 4 and/or 6 kHz will grow quickly over the first few years, and then develop more slowly to reach a maximum level after about 10-15 years. The losses are not expected to exceed 70 dB HL.

- Hearing loss in the lower frequencies takes much longer to develop.

- Once the noise stops, the noise component of the hearing deficit stops growing. Hearing loss due to natural ageing will, of course, continue.

In respect of hearing damage by very high frequency or ultrasonic noise however, there is no such received wisdom. The following sections will review what information is available, while bearing in mind the nature of the hazardous noise and the nature of the hearing deficit. Noise may be of conventional bandwidth, or it may contain VHF or ultrasonic components; the hearing may be affected in the conventional audiometric frequencies, or in the very high frequencies. The options may be structured as a matrix of possibilities:

	conventional wideband occupational noise	noise with VHF and/or ultrasonic components
threshold shift in audiometric freqs, up to 8 kHz	not for consideration here	
threshold shift in VHFs, from 10 kHz upwards		

Conventional noise-induced hearing loss due to conventional noise need not be considered here; each of the other three options may be assessed in the following sections.

3.2.1 Conventional Noise, Threshold Shift in the Very High Frequencies

Sataloff, Vassallo, Menduke (1967)

These investigators sought high-frequency hearing thresholds and configurations in workers with existing noise-induced hearing losses, to be contrasted with thresholds from individuals without noise exposure. All subjects were male employees at a paper mill. Sixty-one noise-exposed workers were selected for the study, but neither noise levels nor durations were given. These exposed workers all exhibited bilateral audiometric notches averaging 30-40 dB at 4 and/or 6 kHz; such configurations were considered consistent with NIHL. Thirty-nine controls were chosen from office staff with no noise exposure or otological problems.

Right-left average hearing thresholds at 10, 12 and 14 kHz were listed for all subjects; this permitted verification that medians were not influenced by truncation of the audiometer output through the insert earphone. For present purposes, the median threshold for each control sub-sample (age band) was subtracted from the corresponding median for the noise-exposed sub-sample. This process, which removes the age factor, gives what might be called ‘excess’ threshold shift for the men with diagnosed noise-induced hearing loss; these ‘excess’ values are given in Table 9.

The noise injury, manifested by a conventional “noise notch” in the audiogram, seems also linked with a constant ‘excess’ threshold shift, at least for 10 and 14 kHz. This excess, if attributable to the hazardous noise, is established in the first few years of exposure. After that, the excess shift does not show any increase with years of employment in the dangerous noise, from just a few years in the youngest group, to more than 20 years in the oldest. At 12 kHz, the trend with age band (a surrogate or proxy variable for years of exposure) is actually the opposite of what might be expected.

Table 9
Excess threshold shifts (dB)
in the noise-exposed workers

Frequency (kHz)	10	12	14
Age range (years)			
20-29	20	38	22
30-39	25	25	23
40-49	22	14	22

Sataloff and his co-workers conclude that hazardous factory noise has a deleterious effect not only on the susceptible frequencies 4 and 6 kHz, but also on the frequencies greater than 8 kHz. This statement should not be taken as the final answer. A wider range of frequencies should be surveyed, and years of noise exposure should be controlled.

Erickson, Fausti, Frey, Rappaport (1980); Fausti et al. (1981a,b)

Hearing sensitivity was measured by earphone, and compared between three groups of subjects, for the conventional range of audiometric frequencies 250 Hz to 8 kHz, and for the extended high frequencies 8 to 20 kHz. Two of the groups had sustained hazardous noise exposure in the military context; the control group had no noise history.

A high-frequency hearing threshold survey was conducted using 100 young adults with normal otological findings, and no history of relevant illnesses or use of ototoxic drugs. Conventional audiometry showed Hearing Threshold Levels of 10 dB or better, with no significant conductive hearing loss. A considerable number of these normal subjects did, however, report limited exposure to popular music, weapons fire, or machinery noise: these individuals were excluded from the study. A purified group of noise-free control subjects, 30 ears from 21 subjects aged 18-27 years, was formed to act as the high-frequency baseline for the study.

The noise-exposed groups were selected from former military personnel aged 20-29 years, with normal otological findings, and no history of relevant illnesses or use of ototoxic drugs. Fourteen had been exposed to impulsive noises from firearms, grenades, mortars or artillery; their audiograms showed irregular/jagged losses, in some cases with great differences between the ears. Twenty-two other subjects were selected for exposure to steady-state noises from aircraft (both flight and ground crew), communications equipment, and more conventional sources.

The authors present their results as output SPLs from the conventional audiometric earphones and from the special high-frequency phones. As before, the data presented here (see Table 10)

Table 10
Threshold shifts for the noise-exposed groups, relative to the normal controls

Frequency (kHz)	0.5	1	2	3	4	6	8	8	10	12	14	16	18	20
	by audiometric earphone							by high-frequency earphone						
normal controls	0	0	0	0	0	0	0	0	0	0	0	0	0	0
steady-state	7	7	5	10	11	17	10	7	6	14	25	45	*	*
impulse	9	9	11	33	58	61	71	62	64	65	66	67	*	*

* insufficient responses, medians not available

are differences of the medians for the groups, to show the relative hearing effects and to avoid equipment-specific influences. The steady-state subjects show a small median hearing loss in the frequencies 3-8 kHz, consistent with a few years of exposure to unspecified noise deemed to be harmful to the hearing. In this group, there appears to be some recovery at 8-10 kHz, with a hearing loss featured for the frequencies 12 kHz and above. The impulse group shows a moderate (and remarkably uniform) hearing loss for all frequencies higher than 3 kHz. It is also worth noting that the highest frequency test tones were inaudible to the majority of the noise-exposed individuals, even at the maximum output of the audiometer.

These data seem to suggest that steady-state noise exposure produces damage in two frequency regions of the cochlea: the widely recognised noise-sensitive 3, 4 and/or 6 kHz, with another region of injury above 12 kHz. Impulse noise injury shows only a single broad region of high frequency damage. However, considerable caution should be exercised. Median (or indeed mean) hearing loss is uninformative in describing the effect of harmful noise of unknown level and duration. In the case of the impulse noise subjects, any measure of central tendency representing asymmetrical hearing losses will hide the true pathology.

This study is really a collection of selected case studies, not chosen in any systematic manner. The authors' results are interesting, but should be considered with circumspection; the data cannot yield any conclusion.

Filipo, de Seta (1983)

These researchers set out to use high-frequency audiometry to show early signs of hearing loss among young workers exposed to hazardous noise. A sample (number not stated) of joiners and carpenters, aged 20-29 years, gave thresholds at 8, 10, 12, ... 18 kHz. These subjects were said to have normal thresholds over the conventional audiometric frequencies in spite of 1-3 years of compulsory military service, and occupational exposure (duration not stated) said to be 95 dB L_{eq}. These workers' high-frequency thresholds were compared to those from 50 subjects of the same age range, but without any noise history. The authors reported no early degradation of the high-frequency thresholds in the noise-exposed subjects.

The investigators have not proved their case. A number of important facts are omitted from the paper, with the result that one cannot judge whether or not the authors' conclusion may be trusted.

Bartsch, Dieroff, Brueckner (1989)

The hearing thresholds of over 500 noise-exposed textile workers was measured for the conventional audiometric frequencies, and for higher frequencies up to 19 kHz. The workers, mostly females, were stratified into ranges of age, daily equivalent noise level, and noise exposure in years. The mean thresholds of several subgroups have been processed for presentation here as threshold shifts for each frequency; see Table 11. Younger workers, aged 17-30 years with a relatively short exposure (up to 10 years, mean 4 y) to presumably harmless noise of 80-84 dB(A), have been chosen as the baseline for the threshold shift of the other workers. Little or no noise-induced hearing loss would be expected in this group; no age-associated loss would be expected either.

Younger workers with 10-20 years (mean 12 y) of textile noise in the range 80-84 dB(A) show little if any shift in the frequencies up to 8 kHz. There is, however, some deterioration for the frequencies 13 kHz and higher, perhaps due to the additional years of age, perhaps to slight

Table 11
Threshold shifts (dB) at the mean, over the entire range of test frequencies, for several of the sub-samples

Frequency (kHz)		0.5	1	2	3	4	6	8	10	11	12	13	14	15	16*	18*
Age	Noise exposure															
17-30 yr	80-84 dB(A) less than 10 yr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	80-84 dB(A) 10-20 yr	-3	-3	-1	0	-1	5	1	4	1	3	5	15	19	8	1
	90-94 dB(A) 10-20 yr	2	1	2	3	7	6	4	4	1	6	16	27	23	25	19
31-60 yr	80-84 dB(A) more than 20 yr	-2	-1	6	10	14	16	15	26	32	45	48	51	43	33	20
	90-94 dB(A) more than 20 yr	7	8	13	24	30	30	23	49	51	59	63	62	49	38	27

* 'Roll-over' values for these frequencies may indicate truncation of responses by maximum output limitation.

noise damage in these very high frequencies. For the younger workers with 10-20 years of noise in the hazardous range 90-94 dB(A), the threshold shift is greater still: a noise effect is plain. A noise-induced hearing loss is present at the noise-sensitive frequencies 4 and 6 kHz, with an excess hearing loss also plain for 16 kHz and higher; this excess must be due to the years of wideband noise exposure.

The pattern is repeated for the workers in the age range 31-60 years: some threshold shift by age and possibly noise for the low-exposure group, but a considerably greater shift for those workers with the higher noise levels. The excess hearing loss due to noise seems to increase with increasing frequency. The trend may not be easily quantified from these data, but it is plain: hazardous noise exposure, capable of causing noise-induced hearing loss in the conventional frequencies, will also damage the hearing for very high frequencies.

Hallmo, Borchgrevink, Mair (1993, 1995); Borchgrevink, Hallmo, Mair (1996)

These researchers examined the high-frequency thresholds given by 167 males, aged 18-59 years, with noise-induced hearing loss in the conventional frequencies up to 8 kHz. All of these men had higher thresholds in the 8-18 kHz range than were recorded for sex- and age-matched subjects without noise exposure; see Hallmo, Sundby, Mair (1994).

The noise-induced hearing losses were placed into one of four categories or “Grades”. Grades I, II and III exhibited mild, moderate and severe hearing deficits, respectively, confined to the noise-sensitive frequencies 3, 4 and 6 kHz. The worst Grade IV showed a widening of the noise notch to include the lower frequencies 1.5 and 2 kHz. Age variation was recognised by separation of the subjects into four age bands: 18-24, 30-39, 40-49 and 50-59 years.

The threshold shift from the normal-for-age values are presented in Table 12. The authors suggest that, for the younger subjects of Grades I and II, a second “dip” may be seen in the audiogram about an octave above the characteristic 3-6 kHz noise notch. Present readers may wish to inspect the Table for a small irregular increase in the threshold shifts between 8 and 12 kHz. For the older subjects and the worse-damaged Grades III and IV, no trends were discernible to the investigators.

Morioka, Miyashita, Gowa, Takeda (1995)

These researchers developed a technique for measuring the upper frequency limit of hearing, and then used their method to determine how the upper limit changed with normal ageing; see Takeda S *et al*. (1992a,b). They then undertook an exploration of the upper frequency limit in cases of occupational noise-induced hearing loss.

Two hundred and thirty-nine male workers participated in the study; 140 worked in factory noise with an equivalent level equal to or greater than 85 dB(A). These workers, exposed to potentially harmful noise, showed worse hearing thresholds than the other portion of the group, who worked in noise less than 85 dB(A). In addition to elevated thresholds in the conventional audiometric frequency range, the exposed workers exhibited a reduction of the upper limit of hearing, greater than the change expected due to natural ageing. Certain frequency boundaries separated the normal population into quartiles for each age band; when these normal boundaries were applied to the noise-exposed sample, the resulting four groups were no longer equal quarters; the distribution of exposed workers was skewed toward reduced upper frequency limits of hearing. The fraction with higher upper limits (best results) was less than one-quarter; the worst fraction contained significantly more than one-quarter of the men.

Table 12
Threshold shifts (excess over age) for the frequencies 8 to 18 kHz, for the four Grades of noise-induced hearing loss; values in parentheses may be subject to truncation of audiometric output.

Frequency (kHz)		8	9	10	11	12	13	14	15	16	17	18
Hearing loss category	Age band (years)											
Grade I	18-24	20	25	20	15	20	20	23	20	25	20	10
	30-39	10	25	10	10	15	30	25	20	15	(10)	(10)
	40-49	20	30	30	30	20	15	0	15	(10)	(5)	—
	50-59	15	20	17	30	15	5	5	(0)	—	—	—
Grade II	18-24	15	20	30	30	20	20	40	30	40	30	10
	30-39	40	45	40	45	45	45	40	25	15	(10)	—
	40-49	38	35	38	38	30	25	15	13	(10)	—	—
	50-59	23	15	17	20	10	5	5	(5)	—	—	—
Grade III	18-24	55	55	53	60	55	55	48	53	48	—	—
	30-39	38	40	50	50	50	45	30	25	15	—	—
	40-49	50	50	50	50	45	35	(20)	(15)	—	—	—
	50-59	45	40	37	30	25	15	5	(5)	—	—	—
Grade IV	18-24	(none of the youngest group had Grade IV hearing losses)										
	30-39	53	68	58	63	53	55	—	—	—	—	—
	40-49	60	60	60	60	—	—	—	—	—	—	—
	50-59	35	35	32	30	15	10	(10)	(5)	—	—	—

The hazardous noise produced elevated hearing thresholds in the conventional audiometric range, and led to a reduction of hearing ability in the very high frequency range. The authors suggest that the upper limit of hearing may serve as a useful form of monitoring audiometry for early identification of NIHL.

Conclusions on conventional noise, VHF threshold shift

The reports seen here suggest that steady-state noise exposure produces damage in two frequency regions of the cochlea: the known noise-sensitive frequencies 3, 4 and/or 6 kHz, with another region of injury beyond the reach of conventional audiometry. After an "island" of noise-resistant hearing at 8-10 kHz, a second noise-sensitive region is found above 12 kHz. One might speculate that some sort of resonance is excited in the tissues of the cochlea, with hair cell death occurring at the areas of maximum displacement or overstimulation. Injury by high-level impulse noise (as by weapons fire) can produce mechanical disruption of cochlear membranes in the regions associated with mid and high frequencies of conventional audiometry; case studies seen here indicate that the VHFs are lost as well.

It is also seen that "ordinary" broadband noise, capable of producing "ordinary" NIHL, will reduce the upper frequency limit of hearing in affected individuals.

These observations may be explained by reference to the organisation of the hair cells within the cochlea. Sound energy of all frequencies enters the inner ear at the basal end of the cochlea and sets up vibratory patterns in the membranes supporting the hair cells. The hair cells at this basal end are the transducers for high frequency sounds; they are, however, subjected to the incoming vibrations for all sounds of whatever frequency, high or low. Hair cells devoted to the very high frequencies would be stimulated to some degree (or overstimulated) by all sound energy entering the cochlea.

3.2.2 Very High Frequency Noise, Conventional Hearing Loss

Grigor'eva (1966)

The extensive use of ultrasonic machinery in Soviet industry raised the question of harmful effects of air-borne ultrasound. Experiments were conducted at the All-Union Central Scientific Research Institute of Occupational Hygiene in Moscow to contrast the physiological effects of tones in the ultrasonic and audible regions.

An unspecified number of subjects were exposed for an hour to a tone of 20 kHz at 110 dB. Tests were made to examine shift of hearing threshold over the frequency range 250 Hz to 10 kHz. Pulse rate, body temperature and skin temperature were also monitored. These tests showed no appreciable effect, even when the Sound Pressure Level was increased to 115 dB. These same subjects were given a one hour exposure to a 5 kHz tone at 90 dB: a considerable TTS was found. The 5 kHz tone at 110 dB produced a powerful vascular response.

These results indicated that air-borne ultrasound is considerably less hazardous than audible sound. A limit of 120 dB was proposed for airborne sound of ultrasonic frequency (presumably 20 kHz or greater). Further TTS experiments were performed to determine acceptable Sound

Pressure Levels for high-frequency tones in the audible region. From these further results, Grigor'eva suggested the following limits:

One-third octave band centre frequency (kHz)	6.3	8	10	12.5	16
Sound Pressure Level (dB)	75	80	85	90	90

It seems safe to infer an underlying concept: A sound which does not produce temporary dullness of hearing cannot produce a permanent noise-induced hearing loss.

Smith (1967)

This author undertook an investigation of TTS produced by exposure to high-frequency noise. The fatiguing noises were bands of filtered white noise, with centre frequencies of 16, 19 and 28 kHz, presented as sound fields with overall Sound Pressure Levels ranging from 85 to 100 dB. Equal numbers of male and female subjects, all with normal hearing, gave pre-test audiograms and then heard the stimuli for 10 minutes. Following the noise exposures, thresholds were again determined, to quantify the shift at 6 kHz. No explanation was given to explain the use of this particular probe tone, to examine the effects of potentially noxious noises of much higher frequency.

The fatiguing exposures followed an unbalanced design, as given below in Table 13 with exposures represented as the bullet (•) symbol. The presentations of noise bands centred at 16 and 28 kHz, heard by 16 subjects, showed no TTS at the probe frequency 6 kHz. The presentations at 19 kHz gave anomalous results, with 24 subjects exhibiting a mean TTS of 15 dB for two conditions, while repeat trials on 16 subjects showed no TTS. The author was unable to explain these contradictory results. He did, however, comment that a number of his subjects showed temporary threshold improvement at 6 kHz after the noise exposures. This phenomenon could be explained more readily by inaccurate pre-test thresholds in the 'improved' individuals, as confirmed by an approximately equal number of instances of slightly degraded thresholds.

Table 13
Smith's noise presentations

Overall SPL (dB)	Band centre frequency (kHz)		
	16	19	28
100	• • •	• • • •	•
95	•		•
90	•		•
85	•		•

In summary, the study showed no systematic TTS at 6 kHz for the noises centred at 16 and 28 kHz. But then, there is no reason to expect a high-frequency noise to produce threshold shift at a lower audiometric frequency.

Acton, Carson (1967)

This investigation was intended to explore the possibility of hearing damage by the noise of industrial ultrasonic equipment. The appliances in question were: drills operating at 20 kHz with maximum one-third-octave band levels in the range 98 to 112 dB; small laboratory washers operating at 16 kHz, band level 91 dB (with an ultrasonic harmonic at 32 kHz, 101 dB); and a bank of large washers operating at 20 kHz, but producing an indistinct spectrum, rising from 75 dB for the 6.3 kHz band to 126 dB for the 40 kHz band.

As discussed above in Section 3.1.1, some operators gave reports of unpleasant subjective effects. In addition, certain of the tool operators gave hearing thresholds at the start and end of a workday on their respective ultrasonic appliances. Thresholds were obtained over the frequency range 2 to 12 kHz, for 31 ears in 16 subjects. No significant TTS was observed in the normal-hearing subjects, so the authors concluded that no permanent NIHL would be expected from the noises of the ultrasonic tools.

Knight (1968)

Eighteen men, workers in the "ultrasonics industry", underwent hearing tests seeking permanent hearing loss which might have been attributable to their occupation. The noise exposure of the subject group was not specified, save for the following unhelpful description: "These men had been engaged for some time on the development and application of cleaning equipment and other ultrasonic apparatus. These machines usually operate at a fundamental frequency in the range 20-40 kHz but they also radiate airborne sound at sub-harmonic frequencies together with wide-band noise from cavitation." Despite his intention of examining the effect of ultrasonic noise, the investigator accepted subjects with potentially hazardous exposure from other noise sources, *e.g.* gunfire, riveting, aero-engines, road drills, and even electric guitars.

The ultrasonic workers gave Hearing Threshold Levels for the audiometric frequencies 250 Hz to 8 kHz. A mean audiogram was presented, showing a slight deficit at 4 kHz; this frequency is widely recognised as showing the first and later most severe effect of (conventional) noise exposure. Thresholds were also presented for a control group of 20 hospital staff of similar age structure but without any noise exposure. The ultrasonic workers were worse by 2 to 7 dB over the entire frequency range. These minimal and non-frequency-specific threshold differences led the investigator to conclude that there was no evidence of hazardous influence of airborne ultrasonic radiation upon the auditory system.

Note: Even if a significant threshold difference had emerged for the vague ultrasonic variable (dichotomous: yes/no), no reliable conclusion would have been possible. The subject samples do not allow one to untangle the confounding between ultrasonic noise (yes/no) and conventional noise (yes/no).

Conclusions on very high frequency noise, conventional hearing loss

The few reports dealing with this noise-and-loss option concentrate on Temporary Threshold Shift from VHF and ultrasonic sounds with levels greater than 100 dB. No TTS was observed. For tones of 8 kHz or less, or for broadband noise, such levels would be expected to result in a considerable dullness of hearing, even after only a few minutes exposure. It seems safe to conclude that, on a straight acoustic pressure or dB basis, VHF or ultrasonic sounds are less hazardous to the hearing than noises confined to the frequency range below 8-10 kHz.

3.2.3 Very High Frequency Noise, Very High Frequency Hearing Loss

Parrack (1966)

Parrack's account of "ultrasonic sickness", seen above at the beginning of this chapter, was accompanied by his more important description of work done in the 1950s, to determine the effect of high frequencies and ultrasound on human hearing. Tones of 17, 21, 24, 26 and 37 kHz were presented individually for five minutes at Sound Pressure Levels in the range 148 to 154 dB. Threshold shifts, usually less than 20 dB, were observed at lower frequencies 8.5, 11, 12, 13, 15 and 18.5 kHz; recovery of pre-test hearing sensitivity at or near these sub-harmonic frequencies was rapid and complete. An opposite effect was observed for similar presentations at 9.2, 10, 12 and 15 kHz: these audible tones produced losses about half an octave higher than the fatiguing tone.

On the basis of these results, Parrack advised that industrial or environmental sound fields in the ultrasonic frequency range should be harmless to the human ear until octave band or one-third octave band levels approach 140 dB. It appears that Parrack's recommendation resurfaced in the ACGIH Threshold Limit Values of 1998, seen in Chapter 2 on Exposure Limits.

Grzesik, Pluta (1986a)

These two investigators looked at how the high-frequency thresholds of 106 workers had been affected by noise from their ultrasonic tools. The subject workers were divided into sub-samples according to noise variables of their exposures: 1) frequency of the maximum-level one-third octave band, and 2) whether that band level was less than 80 dB (deemed harmless) and more than 80 dB (deemed harmful). The workers were also divided in three age bands: 20-29, 30-39 and 40-49 years. Mean thresholds were given for each sub-sample of ultrasonic workers, and for age-matched controls without ultrasonic noise exposure.

For presentation here, the study results have been processed further by subtraction of the control thresholds from those given by each sub-sample of the ultrasonic operators. The resultant variable, termed excess threshold shift (excess over age), is given in Table 14, with Parts a, b and c representing the three sub-samples.

The authors conclude that noise levels greater than 80 dB in the 10, 12.5 and 16 kHz bands "might cause a hearing loss in the range 10 to 16 kHz". However, the exposure durations for each age band cast doubt on even this weak conclusion. Roughly equal exposure time should produce roughly equal threshold shift regardless of age, but this expectation is not met in the data of Parts a and b of Table 14. The shifts of Table 14 Part c are incomplete and have nothing to say regarding any sort of dose-response relation for hearing loss from ultrasonic noise exposure. Indeed, the authors seem not to have considered the possibility that the observed high-frequency threshold shifts might be due to 'ordinary' (not VHF) hazardous noise from the ultrasonic tools. The same criticism may be made of a follow-on paper (1986b) dealing with growth of the VHF hearing decrements of the ultrasonic workers after a further 3 years of exposure. Such a viable alternative hypothesis, hearing loss due to 'ordinary' noise from the ultrasonic tools, is supported by, for instance, Sataloff, Vassallo and Menduke (1967) and by Fausti *et al*. (1981a,b), both reviewed here. Grzesik and Pluta have not proved their case.

Note: These investigators chose 80 dB as the boundary between harmless and harmful. VHF components above this level might be expected to cause unpleasant subjective effects, but without more information the risk to hearing cannot be estimated.

Table 14 Part a
Excess threshold shifts (dB) in the workers whose maximum noise exposure was in 10 kHz band, at a level greater than 80 dB

Frequency (kHz)		10	11	12
Age range (years)	Exposure (years)			
20-29	2.4	1	4	8
30-39	4.6	10	12	16
40-49	4.0	10	9	8

Part b
Excess threshold shifts (dB) in the workers whose maximum noise exposure was in 12.5 kHz band, at a level greater than 80 dB

Frequency (kHz)		11	12	13
Age range (years)	Exposure (years)			
20-29	2.5	2	6	4
30-39	4.4	13	17	19
40-49	3.0	10	9	7

Part c
Excess threshold shifts (dB) in the workers whose maximum noise exposure was in 16 kHz band, at a level greater than 80 dB

Frequency (kHz)		14	15	16
Age range (years)	Exposure (years)			
20-29	2.3	1	5	8
30-39	4.4	12	*	*
40-49	5.0	*	*	*

* data truncated, insufficient responses to calculate mean

Conclusions on VHF noise, VHF hearing loss

There is very little to go on. Parrack was able to produce short-lived TTS in the high-frequency range, using fatiguing ultrasonic tones with extremely high levels, beyond any practical expectation.

Grzesik and Pluta purport to have documented permanent threshold shifts resulting from occupational exposure to the noise of ultrasonic tools, with only a few years of exposure. The levels were said to greater than 80 dB in the VHF bands, but not how much greater. Subjective effects might be expected, but not necessarily hearing damage. The excess hearing losses (excess over age) are small, and shrink as age increases, indicating that natural ageing is the overwhelming influence. However, Grzesik and Pluta have not excluded the possibility that the losses observed are due to the conventional noise exposure of their subjects.

3.2.4 Conclusions on Hearing Loss

It seems that conventional wideband noise, of such a level as to be recognised as an “ordinary” occupational hazard, can cause hearing deficits in the very high frequency range. This is in addition to the predictable hearing damage at 3, 4 and/or 6 kHz. There may be a second region of noise-susceptible frequencies over 12-16 kHz.

Very high frequency noise has not been observed to produce hearing impairment in the conventional audiometric frequencies up to 8 kHz. Therefore, VHF noise has been judged to be somewhat less damaging than an equal level and duration of conventional wideband noise.

Extremely high levels of VHF or ultrasonic noise are capable of producing a degree of hearing loss in the frequencies greater than 8 kHz, beyond conventional audiometry. Of the three exposure options mentioned here, this is the least potent.

In the Introduction to this report, a number of questions were set out for consideration. Several may now be answered, after a fashion.

- Has hearing injury been associated with work situations where a DRC or MPL has been exceeded?

Work situations have been reported to have levels exceeding the DRCs/MPLs for 20 kHz and above. However, acoustic injuries have not been described, reported, or even considered for these workplaces. This is not to say that such hearing injuries do not exist, only that they have not been publicised.

- Has hearing injury been suggested by case studies of single individuals, or investigated more-or-less systematically by survey? Were acoustic conditions reported adequately?

Only Grzesik and Pluta (1986a) purport to describe hearing loss due to very high frequency noise exposure. The reported levels should have caused subjective effects, but the investigators did not consider this aspect of VHF noise. The acoustic exposures were not specified in such a fashion as to pinpoint the supposedly hazardous occupational noise: it could have been the VHF noise from the ultrasonic tools, it might also have been the conventional noise from the tools.

- What is the nature of the suspected / reported auditory dysfunction, e.g. temporary threshold shift, permanent hearing loss, or tinnitus?

Laboratory exposures to extremely high levels of ultrasonic tones can produce temporary threshold shift in the VHFs. Occupational exposures to VHF noise have not shown convincing, systematic hearing loss trends; hearing loss seems to be random in degree, unconnected to exposure duration (in years), and more dominated by age than by noise.

- Is sufficient information available to indicate the prevalence / incidence of hearing injury?

No. It would be inappropriate to suggest a value of prevalence on the basis of a few hundred randomly selected and inadequately described individuals. The literature is little better than a collection of case studies, with no indication of the total number at risk.

- In what frequency range is the effect manifest in human hearing: in the conventional audiometric range up to 8 kHz, or the very high frequencies 10-20 kHz?

Very high frequency noise has been reported to cause minor hearing impairment in the conventional audiometric frequencies up to 8 kHz. Extremely high levels of VHF or ultrasonic noise seem capable of producing a degree of hearing loss in the frequencies greater than 8 kHz. The damage potential of these sounds is very much less than that of conventional sounds of equal level and duration.

- Is there sufficient data available to postulate a dose-response relation, which would be necessary to establish an authoritative noise Exposure Limit?

No. There is not sufficient data in the literature to even contemplate a dose-response relation.

4. HEARING TESTS IN THE VERY HIGH FREQUENCIES

4.1 A CLINICALLY-RECOGNISABLE HEARING PATHOLOGY

In respect of hearing damage by very high frequency or ultrasonic noise however, there is no body of knowledge and experience to suggest audiological findings. However, it is safe to assume that such VHF hearing injury will be sensorineural (located in the cochlea) and bilateral. One may expect that any permanent threshold shift will be related to the exposure parameters SPL and duration, but the growth of any such a hearing loss has not been satisfactorily documented.

In Chapter 3, VHF noise was shown to be associated with hearing impairment in the conventional audiometric frequencies up to 8 kHz. Such VHF noise is somewhat less damaging than an equal level and duration of ordinary wideband noise. In addition, extremely high levels of VHF or ultrasonic noise are capable of producing a degree of hearing loss in the frequencies greater than 8 kHz, beyond the reach of conventional audiometry until quite recently. It remains to be seen if extended high-frequency audiometry will be able to document noise-induced hearing loss in the frequencies beyond 8 kHz. Without reliable measurement of the degree of such loss and its growth over exposure years, it will not be possible to develop a set of useful diagnostic criteria or a dose-response relation, as exists for ordinary hazardous noise.

There are two ways of approaching noise-induced hearing loss in the very high frequencies: decay of the upper frequency limit of hearing, and loss of threshold sensitivity. Both of these changes may be detected by periodic monitoring audiometry using suitable instruments. However, for any such observed changes to be useful markers for VHF or ultrasonic noise injury, they must be somewhat greater that would be expected due to natural ageing.

4.2 AGE-ASSOCIATED VHF HEARING LOSS

The Appendix at the end of this document examines a number of reports to extract information on the age-associated shift of hearing limit and hearing threshold. In the case of the upper frequency limit of hearing, the actual limits may be quoted for age bands of 10 years; the data from different reports seem reasonably well-behaved. For the shift of hearing threshold with age, the SPL values of thresholds for age bands are not usable: the data contain artefacts due to transducer type and calibration method. For present purposes, the results of many studies have been processed to give dB threshold shift, relative to young persons 20-29 years of age. This eliminates the confusing influences of stimulus presentation method and calibration technique.

Table 15 below gives a summary of the upper frequency limit expected for persons in different age bands. The values represent the central tendency of several investigations, and show the steady reduction of the limit with age. However, these middle values will not serve in the individual case, as the testee could be at any (unknown) percentile of the normal-hearing distribution before the start of a potentially hazardous exposure. To detect a developing VHF hearing deficit in a noise-exposed individual, a monitoring programme would be necessary, to document that individual's change over the years. A large change might indicate VHF hearing damage, but at present, there is insufficient information to assess the significance of any change, large or small, random or systematic. Monitoring of the upper limit will probably never be a viable method to detect VHF hearing deterioration due to noise exposure.

Table 15
Summary: Upper frequency limit of hearing by age band

Age band (years)	20-29	30-39	40-49	50-59	60-69	70-79
Frequency (kHz)	17.9	16.7	15.7	14.8	13.8	12.8

The age-associated loss of hearing sensitivity is summarised in Table 16. These centre-of-range data result from critical reading of a number of studies seen in the Appendix, and should be regarded as a first, crude approximation. Inspection of these tentative values shows trends which follow on from the conventional audiometric frequencies up and including 8 kHz. Consider any constant-age row of the Table: as one scans across the row from lower to higher frequencies, the threshold shift (relative to the 20-29 year old baseline) increases. Within any one column, the threshold shift increases with age for the frequency of interest. Threshold shift data for the conventional frequencies suggests that another trend might well be happening in the VHF region: as age or frequency increases, one may expect the distribution of threshold shift (or indeed absolute thresholds) to become more disperse. Such a trend will be seen in the reviews later in this Chapter: it will make diagnosis of VHF hearing injury more difficult.

Table 16
Summary: Threshold shift by age band, relative to persons 20-29 years old

Frequency (kHz)	8	9	10	11	12	13	14	15	16
Age band (years)	Threshold shift (dB)								
20-29	0	0	0	0	0	0	0	0	0
30-39	5	7	7	10	10	11.5	15.4	19	21.5
40-49	10	15	13	20	26.9	33	44	48	38
50-59	24.5	29	35.5	37	50	51	56.5	—	—
60-69	35	48	55	60	70	—	—	—	—

4.3 OUTLOOK FOR HIGH-FREQUENCY AUDIOMETRY: RESEARCH

Laukli, Mair (1985)

A commercially-available audiometer was used to measure the hearing thresholds for frequencies between 8 and 20 kHz, in patient groups and in a small control sample. The data for the control group are of interest here, to show the considerable inter-subject variation amongst even young normal ears.

A group of 30 medical students, aged 20 to 24 years, made up the control or normative group. There were two criteria to join this sample: normal middle ear function, and pure-tone thresholds equal to or better than 20 dB HL for the conventional audiometric frequencies 125 Hz to 8 kHz. A sub-group (n = 12) was also defined as having thresholds of 10 dB HL or better. The VHF thresholds are of little use for present purposes, as the values are dependent upon the transducer employed and its calibration procedure. However, the spread of threshold values does provide some useful information; the threshold range for each frequency is given in Table 16.

Table 16
Range (worst minus best) of thresholds for all ears of the normal or control group, and for the better-hearing sub-group

Frequency, kHz	8	9	10	11	12	13	14	15	16	17	18	19	20
	Range of thresholds (dB)												
All 60 ears	40	40	45	35	45	55	65	65	70	>75*	>60*	>45*	>30*
Best 24 ears	25	25	30	25	35	40	40	50	50	40	40	45	25

* range truncated due to restriction of maximum output from the audiometer

For the whole group of young people, supposedly without hearing pathology, the thresholds cover a range of 35 to more than 75 dB. Such wide variation does not seem compatible with any statement of a reliable threshold for standard-making purposes, or for making any sort of a baseline for cases of possible noise-induced hearing loss manifest in this VHF range.

Frank (1990)

This researcher determined ultra-high-frequency thresholds for 200 ears of 100 normally-hearing adults in the age range 18-28 years. Tones of 10, 12, ... 18 and 20 kHz were presented by an earphone now specified in British and International standards for high-frequency audiometry. The absolute threshold values, in dB Sound Pressure Level measured in a coupler, are of no interest here, especially as the data for the extreme frequencies show considerable truncation due to limitation of audiometer maximum output. The author concentrated his analysis on the variance of thresholds between and within subjects. He found the intrasubject spread (between thresholds on repeat trials) to be quite satisfactory; ± 10 dB was judged acceptable for serial audiometry on any one subject. Intersubject variance was quite another matter, as may be seen in the values below:

Frequency (kHz)	Standard deviation (dB)
10	8.5
12	10.9
14	15.9
16	19.2
18	19.3
20	8.3

The values for 18 and 20 kHz are underestimates due to the truncation of the threshold distribution by non-responders with out-of-range thresholds. Large standard deviations, in the range 16-19 dB, indicate that 95% of thresholds for young normal ears (as from this sample) would be found somewhere within a band 62 to 75 dB wide; such a spread, even amongst normal young ears, would be clinically unacceptable. The author concluded that standardisation of baseline thresholds for normal young ears could not be recommended.

Despite such unfavourable findings from this investigator and others, Reference Equivalent Threshold Sound Pressure Levels have been tentatively standardised for pure tones in the frequency range 8-16 kHz (see BS ISO TR 389-5:1998).

Löppönen, Sorri, Bloigu (1991)

A study was undertaken to determine VHF thresholds by electric bone-conduction audiometry. In all, 208 male and female subjects were tested, without screening tests for admission to the study population. To peg the bone-conduction data to SPL values, VHF air-conduction thresholds were reported as medians, and upper and lower deciles for several age bands. The range between the 10% and 90% thresholds is given in Table 17.

For the youngest group, aged 19-29 years who might be used to establish a Reference Equivalent Threshold Sound Pressure Level for standardisation purposes, the inter-decile ranges are large. Consider the range at 16 kHz: the middle 80% of young persons would have a threshold somewhere in a band 50-60 dB wide. Such a spread is unacceptable for clinical audiometry. An individual at the worse-hearing end of the ‘normal’ range could, in fact, be quite normal or suffering from a substantial hearing deficit. Such a wide range of VHF threshold values leads to indecision, and is not compatible with a useful standardisation of VHF thresholds for audiometry.

Table 17
Indication of the spread of thresholds

Frequency (kHz)	8	10	12	14	16	18
Sex, age range (yrs)	Threshold range (dB) between upper and lower deciles					
males						
19-26	21	25	31	40	50	50
40-41	44	57	69	*	*	*
60-61	74	69	*	*	*	*
females						
18-27	20	25	25	38	60	*
37-43	20	15	30	55	*	*
60-61	50	56	*	*	*	*

* insufficient responses to determine required percentage

Burén, Solem, Laukli (1992)

Pure-tone air-conduction audiometry was performed to determine conventional and high-frequency thresholds for 3 groups of children and young people with median age 10, 14 and 18 years. Subjects were included in the survey if otoscopic examination of the ears showed no signs of past or present ear disease, and if the thresholds over the audiometric frequencies 250 Hz to 2 kHz were found to be 20 dB HL or less. The threshold requirement was relaxed for the higher frequencies 3, 4 and 6 kHz; the researchers wished to include any young subjects with possible noise damage to the hearing

The high-frequency audiometry was performed using a commercially-available audiometer with hi-fi earphones; the equipment and indeed the resultant thresholds are of no interest or present purposes. However, the spread of threshold values in the 17-22 year old subjects does provide some useful information. The 30 males and 39 females of this age group might also be used to establish the audiometric zero for the frequencies 8 to 20 kHz. Of the 69 individuals, 6 had audiometric configurations suggestive of minimal noise-induced hearing loss at 3, 4 and/or 6 kHz, although not all gave a history of any potentially harmful noise exposure.

For the group of 17-22 year olds, the great majority without any hearing pathology, the thresholds covered a range of 60 to 85 dB, over the frequencies 8, 10, 12, ... 20 kHz. This variation, within a seemingly homogeneous group of young people, is somewhat wider than reported above for Laukli and Mair (1985), and seems incompatible with any statement of a useful threshold for standard-making purposes.

4.4 OUTLOOK FOR HIGH-FREQUENCY AUDIOMETRY: STANDARDS

British Standards Institution (1995)

British Standard BS EN 60645-4: 1995 deals with equipment for “extended high-frequency audiometry”. The Standard has two aims:

1. Instrument requirements are stated to cover the frequency range 8-16 kHz, so that extended pure-tone audiometry may be compatible with tests in the lower/conventional frequency range.

2. Extended high-frequency audiometry performed on any given human ear, using different instruments which comply with this Standard, shall give “substantially similar results”.

There are no great electronic demands made by the Standard, save for the requirement of test signals to be spaced at one-third octave intervals: 8, 10, 12.5 and 16 kHz. Intermediate frequencies, if desired, must be interspaced at one-sixth octave intervals: 9, 11.2 and 14 kHz.

Electroacoustic problems may be encountered with the output transducers, either earphones or loudspeakers. The acoustic output of the transducer is measured in dB Hearing Level relative to an ‘audiometric zero’, itself subject to standardisation. The maximum output shall be 90 dB HL or more in the frequency range 8-11.2 kHz, and 50 dB HL or more in the range 12.5-16 kHz. As will be shown below, this permitted restriction of output range has the potential to seriously compromise hearing threshold measurements, possibly for young healthy ears, and certainly for older ears. For example, by referring back to Table 16, one may see that for persons 50-59 years of age the expected centre-of-range threshold shift at 12-13 kHz is approximately 50 dB from young persons of 20-29 years. When tested on an instrument with the minimum specified “headroom” of 50 dB HL, half of normally-hearing 50-59 year olds would have thresholds beyond the range of the instrument; if the older people were a pathological group, perhaps noise-exposed, then an even larger proportion would be untestable at the desired audiometric frequency.

The problems of missing data or truncated range, seen a number of times in Chapter 3 of this document, will continue to occur even though VHF tests of hearing are performed on instruments meeting current national and international standards.

British Standards Institution (1998)

This publication BS ISO TR 389-5: 1998 is a Technical Report from the International Organization for Standardization, issued in the UK by the BSI but not to be regarded as a standard. It is proposed for provisional application; the subject is still under technical development, with the possibility of agreement on an international standard in the future.

This part of ISO 389 specifies the “audiometric zero” for pure tones in the frequency range 8-16 kHz, applicable to the calibration of air-conduction audiometers equipped with any of three specific patterns of earphone. As appropriate to any standard, a number of definitions apply, which may be paraphrased as:

- Equivalent Threshold Sound Pressure Level (ETSPL) - for an individual test ear, at a specified frequency, for a specified pattern of earphone, the SPL output of the phone into a specified calibration cavity/device for the signal corresponding to the threshold of hearing for that one ear

- Reference Equivalent Threshold Sound Pressure Level (RETSPL) - at a specified frequency, the modal value of the ETSPLs of a sufficiently large number of ears of otologically normal persons, of both sexes and aged between 18 and 30 years (inclusive)

- Otologically normal person - an individual in a normal state of health who is free from all signs or symptoms of ear disease and from obstructing wax in the ear canal, and who has no history of undue exposure to noise

RETSPL values are given to allow calibration of audiometer-earphone systems to give 0 dB HL, the “audiometric zero” expected for young normal ears. The standard-making committee expresses the hope that the tentative “zero” will encourage clinical and research workers to produce more threshold data, which will feed back into the standardisation process. It remains to be seen if the demonstrated wide range of threshold values, even for young normal ears, will hinder efforts to agree a practical standard for VHF hearing testing.

4.5 CONCLUSIONS ON VHF HEARING TESTS

It is now possible to attempt an answer to the last question posed at the outset of this review project:

- Can hearing loss, either noise-induced or age-associated, be reliably measured in the frequencies beyond the audiometric range?

The design and manufacture of audiometric instruments for VHF testing has reached such a state that standards have been set, indicating an international consensus of best available practice. Several earphones have been specified for use with the instruments, and a tentative “audiometric zero” has been proposed for each phone. This state of affairs is not an endpoint, but rather a beginning. Hearing researchers now have convenient equipment for VHF testing: much work needs to be done using these instruments.

Research is needed to document the distribution of young normal hearing thresholds in the VHF range, as determined using the tentative “audiometric zero” for VHF earphones. If the range is found to be relatively narrow, perhaps 30 dB to cover the expected range from acute to dull hearing, then VHF audiometry may be deemed reliable for young normal ears. Such a narrow range of threshold values for a homogeneous population of healthy ears suggests a useful future role to play in the description of normal and damaged hearing in older ears. From such a starting point, the influence of natural ageing should be documented in otologically normal older persons; medians and fractiles are needed for each decade of age. With knowledge of the distribution of VHF thresholds for normal ageing, it should be possible to judge statistically the effect of any potentially harmful influence, for instance noise, in a non-normal individual.

5. CONCLUSIONS

At the beginning of this report, a number of questions were posed. A question and answer format will set out the present state of knowledge; negative answers may point to necessary further work.

- What Damage Risk Criteria or Maximum Permissible Levels are there which deal specifically with noise of very high frequency or ultrasonic frequency?

There are a number of Damage Risk Criteria and Maximum Permissible Limits first recommended by research organisations and individuals, and later adopted by governmental bodies and by international organisations. It seems that Soviet, UK and American investigators of the 1960s took a reasoned approach, recommending DRCs and MPLs supported by limited experimental and survey data. These tentative first recommendations were then taken up by national and international bodies, to gain authority by repetition: the idea of 'proposed' or 'tentative' has been lost in the repetitions.

- How do these limits compare, in terms of maximum permissible level and duration?

The limits reviewed here are typically given as SPLs for one-third-octave bands from 10 kHz upwards past 20 kHz. Different MPLs apply in two distinct regions, to satisfy different aims. For the very high frequencies, 10-20 kHz, the limits were set at band levels in the range 75-85 dB, to avoid unpleasant subjective effects such as annoyance and auditory discomfort, tinnitus, balance disturbance, persistent headaches, fatigue, malaise and even nausea. Considering how the young, normal threshold of hearing increases sharply over the range 10-20 kHz, the MPLs of 75-85 dB represent modest loudness. For older persons, with a degree of age-associated hearing deterioration in these high frequencies, the typical limit value of 80 dB would seem somewhat quieter, possibly even inaudible.

When occupational exposure to VHF noise and ultrasound was being explored in the 1960s, subjective effects were sought from a quite limited population of exposed workers; in some cases, the research workers combined their own observations with those of their subject-workers. Very little has appeared in the literature since those tentative reports, although it would seem safe to assume that the subjective effects have not gone away in the meantime. A structured survey of effects, linked to measured VHF band levels, would be helpful in confirming (or otherwise) the long-established MPLs for unprotected ears. A second aim might be determination of the prevalence of unpleasant subjective effects at various levels of VHF or ultrasonic noise; this might be thought of as work towards a dose-response relation describing adverse subjective effects.

For ultrasonic components 20 kHz and above, DRCs were specified to avoid hearing damage in the audible (lower) frequencies. Such damage would take the form of Temporary Threshold Shift on a daily basis, possibly leading to permanent NIHL over years of occupational exposure. However, the maximum acceptable one-third-octave band levels of 105-115 dB had been demonstrated to produce no hearing deficit. Without information to suggest that the band levels are over-protective, there seems little reason to relax the DRCs.

Turning from maximum acceptable levels, there is also a range of view regarding the influence of time, as it is related to exposure dose. None of the DRCs seen here have a fully-developed

Exposure Level, calculated from the variables SPL and noise duration, on a daily basis repeated over working years. Where duration is considered at all, there is a trading relationship broadly in line with equal-energy considerations: halving of noise duration allows a 3 dB increase in level. However, the band limits seen here have two stated aims: to avoid subjective effects and to avoid TTS and NIHL. In particularly sensitive individuals, unpleasant subjective effects might be expected to appear shortly after the start of a VHF or ultrasonic noise exposure. An increase of permitted band level, in line with a daily duration correction, may be expected to hasten the onset of adverse subjective effects in sensitive individuals, and possibly to involve a larger proportion of the exposed population. Both of these outcomes are undesirable: any duration supplement works to thwart one stated aim of the limit.

- Do the various DRCs indicate a degree of intended protection, that is, what percent of the exposed population is protected against what hearing loss "low fence"?

On this point, all of the limits and recommendations reviewed here take the most extreme view possible on intended protection. The MPLs have been set to avoid any subjective effects and *any* auditory effects, in *any* exposed individuals.

In respect of hearing damage by noise, the concept of intended protection requires detailed knowledge of the noise dose (level and duration) required to produce a hearing damage response over the range of susceptible individuals. There have been no useful studies of the dose-response relation for VHF or ultrasonic noise. Well-controlled occupational surveys are unlikely to be undertaken; a range of dangerous noises in the workplace will be difficult to find, and changing attitudes to work suggest that long (unprotected) exposures will be rare.

- Has hearing injury been associated with work situations where a DRC or MPL has been exceeded?

- What is the nature of the suspected / reported auditory dysfunction, e.g. temporary threshold shift, permanent hearing loss, or tinnitus?

- Has hearing injury been suggested by case studies of single individuals, or investigated more-or-less systematically by survey? Were acoustic conditions reported adequately?

These questions may be considered together. There are a very few reports of permanent hearing loss in workers exposed to noise of very high or ultrasonic frequency. Few workers are represented, and none with daily contact with potentially harmful noise for more than five years or so. Daily exposure conditions are not described sufficiently to judge if any recognised DRC or MPL had been exceeded, or to estimate noise dose. No consideration was given to the possibility that the reported VHF hearing losses might be the result of broadband conventional noise from the workplace tools or appliances.

In respect of temporary threshold shift and tinnitus, the situation is somewhat brighter due to the work of the 1960s which lead to the DRCs and MPLs discussed above. Case studies reported the one-third-octave band levels of workers exposed for several hours per day to the noise of ultrasonic tools; no instances of TTS were observed, so the highest observed levels were recommended as safe. Tinnitus was treated as a subjective effect, but more properly should be viewed as a form of auditory dysfunction, being generated somewhere in the human hearing system as a response to the acoustic stimuli. The MPLs over 10-20 kHz were set with the purpose of avoiding tinnitus, as only one of the unpleasant subjective effects.

- Is sufficient information available to indicate the prevalence / incidence of hearing injury?

The answer here is quite plainly no. No study or survey reviewed here gave any information on the number of workers exposed and the number suffering a degree of hearing injury or dysfunction as result of that exposure. The same may be said for the various subjective effects.

- In what frequency range is the effect manifest in human hearing: in the conventional audiometric range up to 8 kHz, or the very high frequencies 10-20 kHz?

- Are there recognised clinical features which would support a diagnosis of very-high-frequency noise-induced hearing loss?

Occupational exposures to VHF noise have not shown convincing, systematic hearing loss trends; the reported hearing deficits seem to show little regularity in respect of frequency and degree of loss. The deficits are unconnected to exposure duration (in years), and more dominated by age than by noise. To make matters worse, it seems that conventional wideband noise, of such a level as to be recognised as an "ordinary" occupational hazard, can cause hearing loss in the very high frequency range. This is in addition to the predictable hearing damage at 3, 4 and/or 6 kHz. There may be a second region of noise-susceptible frequencies over 12-16 kHz.

In the face of such poor prospects for a recognisable diagnostic feature for VHF hearing loss, one might ask:

- Can hearing loss, either noise-induced or age-associated, be reliably measured in the frequencies beyond the audiometric range?

Audiometric equipment is now available to perform VHF testing conveniently, in a standard fashion against a widely-known audiometric zero. However, it remains to be seen whether, for any large homogeneous subject sample, the distribution of thresholds will be widely dispersed or relatively compact. If between-subject variance of threshold is wide, even for otologically normal young people, then VHF audiometry has limited usefulness save for regularly-repeated monitoring audiometry to identify growing pathology (as might be caused by noise exposure). If within-subject variance is also large, indicating poor repeatability, then VHF audiometry will have no use whatever.

On the other hand, if threshold variance is relatively narrow for samples with increasing age, then the effect of hazardous noise exposure may be statistically distinguishable in exposed populations. The response term of a dose-response relation would be accessible.

- Is there sufficient data available to postulate a dose-response relation, which would be necessary to establish an authoritative noise Exposure Limit?

No. There is not sufficient data in the literature to support, or even contemplate, a dose-response relation between occupational exposure to VHF noise and resultant hearing risk.

Recommendations for Further Work

Over the frequency range 10-20 kHz, the MPLs were set at band levels in the range 75-85 dB, to avoid unpleasant subjective effects such as annoyance and auditory discomfort, tinnitus, balance disturbance, persistent headaches, fatigue, malaise and even nausea. A structured survey of effects, linked to measured VHF band levels, would be helpful in confirming (or otherwise) these long-established MPLs for unprotected ears. A second aim might be determination of the prevalence of unpleasant subjective effects at various levels of VHF or ultrasonic noise; this might be thought of as work towards a dose-response relation describing adverse subjective effects.

It is too early to think of a dose-response relation for hearing injury. There are foundation stones to be put in place first. A census is needed to determine how many ultrasonic tools and appliances are in use throughout the United Kingdom, and how many workers are exposed to the acoustic output of these devices? Is the number exposed workers growing or shrinking? A representative sample of the tools should be chosen for acoustic survey; frequency analysis of acoustic output should be aimed at identifying those devices with dangerous conventional noise and/or ultrasonic components at potentially harmful levels. Again, how many ultrasonic workers are subject to these potentially harmful sounds, and for how long each workday? These answers to these questions will permit a first assessment of the scale of any problem which might exist. Once the population at risk has been quantified, paths for future research may be opened or abandoned.

Large numbers at risk, perhaps several thousand workers in the present industry or that expected in the foreseeable future, would make it worthwhile to plan for a dose-response relation.

If the UK population of ultrasonic workers numbers only a few hundred, then hope of a dose-response relation must be abandoned. Such a small total population would yield unworkably small sub-sets by age, years of exposure, and noise level (both A-weighted Sound Level and ultrasonic band levels). On the other hand, a small population could be an opportunity. A total population of a few hundred workers opens the possibility of a complete acoustic and audiological description of the industry.

6. REFERENCES

Note: All of the documents given here deal with VHF noise or ultrasound, and their effects on human hearing. All were consulted, but not all were included in this literature review.

ACGIH. 1998 TLVs and BEIs Threshold Limit Values for chemical substances and physical agents, Biological Exposure Indices. American Conference of Governmental Industrial Hygienists, Cincinnati, Ohio, 1998.

Acton WI. A criterion for the prediction of auditory and subjective effects due to air-borne noise from ultrasonic sources. Annals Occupational Hygiene 1968; 11: 227-234.

Acton WI. The effects of airborne ultrasound and near-ultrasound. In: Ward WD (ed.) Proceedings International Congress on Noise as a Public Health Problem, Dubrovnik, May 1973; Document 550/9-73-008, US Environmental Protection Agency, Washington DC: 349-359.

Acton WI. The effects of industrial airborne ultrasound on humans. Ultrasonics 1974; 12: 124-128.

Acton WI. Exposure criteria for industrial ultrasound. Annals Occupational Hygiene 1975; 18: 267-268.

Acton WI. Exposure criteria for industrial ultrasound. Ultrasonics 1976; 14: 42.

Acton WI. Exposure to industrial ultrasound: Hazards, appraisal and control. Journal Society Occupational Medicine 1983; 33: 107-113.

Acton WI, Carson MB. Auditory and subjective effects of airborne noise from industrial ultrasonic sources. British Journal Industrial Medicine 1967; 24: 297-304.

Acton WI, Hill CR. Hazards of industrial ultrasound. Protection 1977; 12, 15-16.

auf der Maur AN. Limits for exposure to airborne ultrasound. Annals American Conference Industrial Hygienists 1985; 12: 177-181.

Bahannan S, el-Hamid AA, Bahnassy A. Noise level of dental handpieces and laboratory engines. Journal Prosthetic Dentistry 1993; 70: 356-360.

Bartsch R, Dieroff HG, Brueckner C. High-frequency audiometry in the evaluation of critical noise intensity. International Archives Occupational Environmental Health 1989; 61: 347-351.

Behar A, Crabtree RB. Measurement of hearing protector attenuation at ultrasonic frequencies. In: Burroughs CB (ed.), Proceedings Noise-Con 97, Pennsylvania State University, June 1997; 1: 97-102.

Berger EH. Attenuation of hearing protectors at the frequency extremes. 11th International Congress on Acoustics, Paris, 1983; 3: 289-292.

Berger EH. Protection from infrasonic and ultrasonic noise exposure. Earlog 14, 1984; EAR Division, Cabot Corporation, Indianapolis, Indiana.

Borchgrevink HM, Hallmo P, Mair IWS. Extended high-frequency hearing loss from noise exposure. Chapter 24 in: Axelsson A *et al* (eds.), Scientific basis for noise-induced hearing loss. Thieme, New York, 1996.

British Standards Institution. Normal equal-loudness level contours for pure tones under free-field listening conditions. BS 3383: 1988. British Standards Institution, London.

British Standards Institution. Audiometers Part 4: Equipment for extended high-frequency audiometry. BS EN 60645-4: 1995. British Standards Institution, London.

British Standards Institution. Acoustics – Reference zero for the calibration of audiometric equipment – Part 5: Reference equivalent sound pressure levels for pure tones in the frequency range 8 kHz to 16 kHz. BS ISO TR 389-5:1998. British Standards Institution, London.

British Standards Institution. Acoustics – Reference zero for the calibration of audiometric equipment – Part 7: Reference threshold of hearing under free-field and diffuse-field listening conditions. BS EN ISO 389-7:1998. British Standards Institution, London.

British Standards Institution. Electroacoustics – Simulators of human head and ear – Part 2: An interim acoustic coupler for the calibration of audiometric earphones in the extended high-frequency range. BS EN 60318-2:1998. British Standards Institution, London.

British Standards Institution. Filters for the measurement of audible sound in the presence of ultrasound. BS EN 61012:1998. British Standards Institution, London.

Brown GG. Airborne ultrasonics ... their effects upon humans. Canadian Hospital 1967; 44: 55-56.

Brüel PV. Limits for infrasound and ultrasound in factories. In: Czarnecki S (ed.) Proceedings Inter · Noise 79, Warsaw, September 1979; 2: 849-854.

Bryan ME, Tempest W. Hearing above 20 kHz. Sound 1970; 4: 67-71.

Burén M, Solem BS, Laukli E. Threshold of hearing (0.125-20 kHz) in children and youngsters. British Journal Audiology 1992; 26: 23-31.

Coles RRA, Hoare NW. Noise-induced hearing loss and the dentist. British Dental Journal 1985; 159: 209-218.

Crabtree RB, Behar A. Measurement of hearing protector insertion loss at ultrasonic frequencies. Applied Acoustics 2000; 59: 287-299.

Cracknell AP. Ultrasonics. Wykeham Publications, London, 1980.

Damongeot A, André G. Low frequency ultrasound: Effects and limits. Proceedings Inter · Noise 85, Munich, September 1985; 2: 1049-1052.

Damongeot A, André G. Noise from ultrasonic welding machines: Risks and prevention. Applied Acoustics 1988; 25: 49-66.

Dawson C *et al.* Does lithotripsy cause hearing loss? British Journal Urology 1994; 73: 129-135.

De Seta E, Bertoli GA, Filipo R. High-frequency audiometry above 8 kHz: Comparative results of normative thresholds obtained with a headphone system and a quasi-free-field system. Audiology 1985; 24: 254-259.

Dickson EDD. Some effects of intense sound and ultrasound on the ear. Proceedings of the Royal Society of Medicine 1953; 46: 139-148.

Dieroff H-G. Behaviour of high-frequency hearing in noise. Audiology 1982; 21: 83-92.

Dobroserdov VK. The effect of low frequency ultrasound and high frequency sound on exposed workers. Occupational Safety Health Abstracts 1967; 5: 658 (abstract).

Erickson DA, Fausti SA, Frey RH, Rappaport BZ. Effects of steady-state noise upon human hearing sensitivity from 8000 to 20 000 Hz. American Industrial Hygiene Association Journal 1980; 41: 427-432.

Fausti SA *et al*. The effects of impulsive noise upon human hearing sensitivity (8 to 20 kHz). Scandinavian Audiology 1981a; 10: 21-29.

Fausti SA *et al*. The effects of noise upon human hearing sensitivity from 8 000 to 20 000 Hz. Journal Acoustical Society America 1981b; 69: 1343-1349.

Filipo R, De Seta E. Ultra-audiometric study of ‘normal’ noise-exposed listeners. Proceedings Fourth International Congress on Noise as a Public Health Problem, Turin, June 1983; 1: 353-356.

Fletcher JL. A history of high-frequency hearing research and application. Seminars Hearing 1985; 6: 325-329.

Flottorp G. Effects of noise upon the upper frequency limit of hearing. Acta Otolaryngologica 1973; 75: 329-331.

Forman-Franco B, Abramson AL, Stein T. High-speed drill noise and hearing: Audiometric survey of 70 dentists. Journal American Dental Association 1978; 97: 479-482.

Frank T. High-frequency hearing thresholds in young adults using a commercially available audiometer. Ear Hearing 1990; 11: 450-454.

Frisman FF. On the question of occupational hygiene and pathology in the industrial application of ultrasound. Ultrasonics 1963; 1: 237 (book review).

Grigor’eva VM. Effect of ultrasonic vibrations on personnel working with ultrasonic equipment. Soviet Physics - Acoustics 1966; 11: 426-427.

Grigoreva V. Ultrasound and the question of occupational hazards. Ultrasonics 1966; 4: 214 (abstract).

Grzesik J, Pluta E. Noise and airborne ultrasound exposure in the industrial environment. In: Tobias JV *et al* (eds.), Proceedings Third International Conference on Noise as a Public Health Problem, Freiburg, September 1978; ASHA Reports 10, American Speech-Language-Hearing Association, Rockville, Maryland, 1980.

Grzesik J, Pluta E. High-frequency hearing risk of operators of ultrasonic devices. International Archives Occupational Environmental Health 1983; 53: 77-88.

Grzesik J, Pluta E. High-frequency noise-induced hearing loss: a field study on the roll of intensity level and accumulated noise dose. International Archives Occupational Environmental Health 1986a; 57: 127-136.

Grzesik J, Pluta E. Dynamics of high-frequency hearing loss of operators of industrial ultrasonic devices. International Archives Occupational Environmental Health 1986b; 57: 137-142.

Hallmo P, Borchgrevink HM, Mair IWS. High-frequency thresholds: Extensive loss above 2 kHz for impulsive noise exceeding a critical level? Proceedings Sixth International Congress on Noise as a Public Health Problem, Nice, July 1993; 2: 53-56.

Hallmo P, Sundby A, Mair IWS. Extended high-frequency audiometry: Air- and bone-conduction thresholds, age and gender variations. Scandinavian Audiology 1994; 23: 165-170.

Hallmo P, Borchgrevink HM, Mair IWS. Extended high-frequency thresholds in noise-induced hearing loss. Scandinavian Audiology 1995; 24: 46-52.

Han LA, Poulsen T. Equivalent threshold sound pressure levels for Sennheiser HDA 200 earphone and Etymotic Research ER-2 insert earphone in the frequency range 125 Hz to 16 kHz. Scandinavian Audiology 1998; 27:105-112.

Health Canada. Guidelines for the safe use of ultrasound: Part II Industrial and commercial applications Safety Code 24. Document EHD-TR-158, 1991; Health Protection Branch, Environmental Health Directorate, National Health and Welfare, Canada.

Henry KR, Fast GA. Ultrahigh-frequency auditory thresholds in young adults: Reliable responses up to 24 kHz with a quasi-free-field technique. Audiology 1984; 23: 477-489.

Herbertz J. Loudness of airborne ultrasonic noise. Proceedings Ultrasonics International 83, Halifax, Nova Scotia, July 1983; 226-231.

Herman BA, Powell D. Airborne ultrasound: Measurement and possible adverse effects. HHS Publication (FDA) 81-8163, US Department of Health and Human Services, Food and Drug Administration, Rockville, Maryland, 1981.

Hill CR, ter Haar G. Ultrasound. Chapter 6 in: Suess MJ (ed.) Nonionizing Radiation Protection. WHO Regional Publications European Series No. 10, World Health Organization Regional Office for Europe, Copenhagen, 1982.

Hill CR, ter Haar G. Ultrasound. Chapter 6 in: Suess MJ, Benwell-Morrison DA (eds.) Nonionizing Radiation Protection, second edition. WHO Regional Publications European Series No. 25, World Health Organization Regional Office for Europe, Copenhagen, 1989.

Holmberg K, Landström U, Nordström B. Annoyance and discomfort during exposure to high-frequency noise from an ultrasonic washer. Perceptual Motor Skills 1995; 81: 819-827.

Holmes J. Noise exposure in the dental surgery aboard HMS Illustrious. INM Technical Report (Health & Hygiene) No. 98036. Institute of Naval Medicine, Gosport, Hants, 1998.

International Electrotechnical Commission. Sound level meters. IEC 651, 1979. Bureau Central de la Commission Electrotechnique Internationale, Geneva.

International Labour Office. Protection of workers against noise and vibration in the working environment. ILO Code of Practice, 1977; International Labour Office, Geneva.

International Non-Ionizing Radiation Committee, International Radiation Protection Association. Interim guidelines on limits of human exposure to airborne ultrasound. Health Physics 1984; 46: 969-974.

International Organization for Standardization. Normal equal-loudness contours for pure tones and normal threshold of hearing under free field listening conditions. ISO/R226-1961. International Organization for Standardization, Geneva.

International Organization for Standardization. Acoustics - Normal equal-loudness contours. ISO 226: 1987. International Organization for Standardization, Geneva.

Knight JJ. Effects of airborne ultrasound on man. Ultrasonics 1968; 6: 39-42.

Körpert K, Vanek R. Application of two exposure criteria to different types of industrial ultrasound. Proceedings Ultrasonics International 87, London, July 1987; 232-237.

Laukli E, Mair IWS. High-frequency audiometry: Normative studies and preliminary experiences. Scandinavian Audiology 1985; 14: 151-158.

Lee HK. Health hazards of occupational exposure to airborne ultrasound. Occupational Health Technical Memorandum No. 6; 1980. Health and Welfare Canada, Medical Services Branch.

Lehto TU *et al*. Hearing of dentists in the long run: a 15-year follow-up study. Community Dentistry Oral Epidemiology 1989; 17: 207-211.

Lehto T. Dentists' hearing and exposure to high speed turbine dental drill noise. Proceedings Finnish Dental Society 1990; 86: 115-125.

Löppönen H, Sorri M, Bloigu R. High-frequency air-conduction and electric bone-conduction audiometry: Age and sex variations. Scandinavian Audiology 1991; 20: 181-189.

Man A, Neuman H, Assif D. Effects of turbine dental drill noise on dentists' hearing. Israel Journal Medical Sciences 1982; 18: 475-477.

Mason RK. Asthma and high frequency sound perception. Nature 1967; 214: 99-100.

Morioka I, Miyashita K, Gowa Y, Takeda S. Evaluation of noise-induced hearing loss by reference to the upper limit of hearing. International Archives Occupational Environmental Health 1995; 67: 301-304.

Northern JL *et al*. Recommended high-frequency audiometric threshold levels (8000-18 000 Hz). Journal Acoustical Society America 1972; 52: 585-595.

Northern JL, Ratkiewicz B. The quest for high-frequency normative data. Seminars Hearing 1985; 6: 331-339.

Osterhammel D. High-frequency thresholds using a quasi-free-field technique. Scandinavian Audiology 1978; 7: 27-30.

Osterhammel D. High-frequency audiometry and noise-induced hearing loss. Scandinavian Audiology 1979; 8: 85-90.

Osterhammel D, Osterhammel P. High-frequency audiometry: Age and sex variations. Scandinavian Audiology 1979; 8: 73-81.

Osterhammel D, Osterhammel PA. High-frequency thresholds using a quasi-free-field transducer. Seminars Hearing 1985; 6: 341-346.

Osterhammel D, Osterhammel P, Terkildsen K. A quasi-free-field transducer system for high-frequency audiometry. Scandinavian Audiology 1977; 6: 91-95.

Parrack HO. Effect of air-borne ultrasound on humans. International Audiology 1966; 5: 294-308

Poulsen T, Han LA. The binaural free field hearing threshold for pure tones from 125 Hz to 16 kHz. Acustica 2000; 86: 333-337.

Rahko AA, Karma PH, Rahko KT, Kataja MJ. High-frequency hearing of dental personnel. Community Dentistry Oral Epidemiology 1988; 16:268-270.

Ribári O, Kiss JG. Early detection of hearing damage by high-tone audiometry. Proceedings Fourth International Congress on Noise as a Public Health Problem, Turin, June 1983; 1: 221-229.

Roberts ME. Report of a hearing survey of dentists. Journal Canadian Dental Association 1978; 3: 110-113.

Robertson RM, Williams CE. Effect of noise exposure during primary flight training on the conventional and high-frequency hearing of student pilots. Aviation Space Environmental Medicine 1975; 46: 717-724.

Roscin IV *et al*. Occupational health hazards of technical applications of ultrasound. Occupational Safety Health Abstracts 1967; 5: 657 (abstract).

Rosen S *et al*. High frequency audiometry in presbycusis. Archives of Otolaryngology 1964; 79: 18-32.

Sakamoto M, Sugasawa M, Kaga K, Kamio T. Average thresholds in the 8 to 20 kHz range in young adults. Scandinavian Audiology 1998; 27: 169-172.

Sakamoto M, Sugasawa M, Kaga K, Kamio T. Average thresholds in the 8 to 20 kHz range as a function of age. Scandinavian Audiology 1998; 27: 189-192.

Sataloff J, Vassallo L, Menduke H. Occupational hearing loss and high frequency thresholds. Archives Environmental Health 1967; 14: 832-836.

Skillern CP. Human response to measured sound pressure levels from ultrasonic devices. American Industrial Hygiene Association Journal 1965; 26: 132-136.

Skurr BA, Bulteau VG. Dentists' hearing: The effect of high speed drill. Australian Dental Journal 1970; 15: 259-260.

Smith PE Jr. Temporary threshold shift produced by exposure to high-frequency noise. American Industrial Hygiene Association Journal 1967; 28: 447-451.

Stelmachowicz PG, Beauchaine KA, Kalberer A, Jesteadt W. Normative thresholds in the 8- to 20-kHz range as a function of age. Journal Acoustical Society America 1989; 86: 1384-1391.

Takeda S *et al*. Testing procedure for measuring the upper limit of hearing. Wakayama Medical Report 1992a; 33: 77-87.

Takeda S *et al*. Age variation in the upper limit of hearing. European Journal Applied Physiology 1992b; 65: 403-408.

Takeshima H *et al*. Threshold of hearing for pure tone under free-field listening conditions. Journal Acoustical Society Japan (E) 1994; 15: 159-169.

Taylor W, Pearson J, Mair A. The hearing threshold levels of dental practitioners exposed to air turbine drill noise. British Dental Journal 1965; 118: 206-210.

Teigland CM, Clayman RV, Winfield HN, Roeser RJ. Ultrasonic lithotripsy: The risk of hearing loss. Journal Urology 1986; 135: 728-729.

Townsend TH, Bess FH. High frequency attenuation characteristics of ear protectors. Journal Occupational Medicine 1973; 15: 888-891.

United Nations Environment Programme, World Health Organization, International Radiation Protection Association. Ultrasound: Environmental Health Criteria 22. World Health Organization, Geneva, 1982.

Walmsley AD, Hickson FS, Laird WRE, Williams AR. Investigation into patients' hearing following ultrasonic scaling. British Dental Journal 1987; 162: 221-224.

Ward WD, Holmberg CJ. Effects of high-speed drill noise and gunfire on dentists' hearing. Journal American Dental Association 1969; 70: 1383-1387.

Weatherton MA, Melton RA, Burns WW. The effect of dental drill noise on the hearing of dentists. Journal Tennessee Dental Association 1972; 52: 305-308.

Wiernicki C, Karoly WJ. Ultrasound: Biological effects and industrial hygiene concerns. American Industrial Hygiene Association Journal 1985; 46: 488-496.

Wiley TL *et al*. Aging and high-frequency hearing sensitivity. Journal Speech Language Hearing Research 1998; 41: 1061-1072.

Wilson CE *et al*. Hearing-damage risk and communication interference in dental practice. Journal Dental Research 1990; 69: 489-493.

Zubick HH, Tolentino AT, Boffa J. Hearing loss and the high speed dental handpiece. American Journal Public Health 1980; 70: 633-635.

APPENDIX

AGE-ASSOCIATED HEARING LOSS IN THE VERY HIGH FREQUENCIES

A1 INTRODUCTORY NOTES

The main purpose of the present document is to consider what hearing loss might be caused by repeated exposure to noises with components of very high frequency or ultrasonic frequency. To recognise such hearing damage, one must know how the hearing function changes with age, either by reduction of the upper limit of hearing or the loss of hearing sensitivity in the relevant frequencies. In noise-exposed individuals, any change greater than that expected for natural ageing may be considered a possible manifestation of hearing impairment by the noise.

For the conventional audiometric frequencies, up to 8 kHz, age-related hearing loss is well-documented for the otologically normal population and for unscreened ‘typical’ populations. Such losses are reported as threshold shift relative to young persons, usually 18 years old. For frequencies beyond 8 kHz, information on age-associated hearing loss does exist but is scattered thinly throughout the relevant literature. This Appendix brings together the various reports in a fashion helpful to one main aim of this document: recognising excess hearing loss which might be caused by noise exposure.

There are a number of studies which report on VHF hearing thresholds and upper limits, determined by a variety of presentation methods including:

1. Free-field presumably in an anechoic test environment; free progressive waves pass by both ears simultaneously, from a distant source directly ahead of the listener (zero degrees azimuth and elevation);
2. Quasi-free-field from a source close to one ear of the listener, either in front of the head or aimed at the test ear from one side (90 or 270 degrees azimuth);
3. Earphone fitted with a condenser microphone as the transducer;
4. Conventional “hi-fi” earphones capable of VHF output; or
5. Ear insert, with VHF signals conveyed to the (sealed) ear canal by means of a narrow tube.

Each of these disparate presentation methods has appeared in the relevant literature, with results given as Sound Pressure Levels determined by some calibration method. In the case of field methods, the levels are measured at the ear location, but with the listener’s head absent. For the earphone and insert methods, a calibration cavity is employed; the calibration device may be standardised or purpose-built. As might be expected, the reported threshold values differ between investigations and distract the reader from the desired information, that is, shift of threshold with age. For present purposes, the results of many studies have been processed to give dB threshold shift, relative to young persons 20-29 years of age. This eliminates the confusing influences of stimulus presentation method and calibration method.

A2 UPPER FREQUENCY LIMIT OF HEARING

Mason (1967)

This investigator was attracted to the notion that asthma sufferers may be particularly sensitive to some physical stimuli, and set out to look for an unusual sensitivity to high-frequency sound. The subjects for this study were 47 asthmatics of varying age; as controls, 25 children and 35 adults were enlisted from the asthmatics' families. The data from these typical, unscreened adult controls are of interest here.

Frontally-incident pure tones were presented to each subject, for determination of hearing thresholds starting at 8 kHz and progressing in steps of 1 kHz until no response was elicited, even at the (unstated) maximum output of the sound reproduction system. The highest frequency perceived was taken to be the upper frequency limit of hearing for that subject.

The upper limit results were presented graphically, with age and frequency as the independent and dependent variables, respectively. No trend lines were given by the author, so the present reviewer drew an "eyeball" curve through the points representing the control subjects. The upper limits by age band are approximated as:

20-29 years	17.5 kHz
30-39	15.5
40-49	13.5

Note: The asthmatics did seem to have hearing which ranged to frequencies higher than perceived by their non-asthmatic relatives.

Robertson, Williams (1975)

This investigation looked for high-frequency noise-induced hearing loss in student pilots, possibly attributable to noise exposure during military flight training. One hundred and eight student pilots, aged 21 to 28 years, gave hearing thresholds for the frequencies 4-18 kHz, both before and after training comprising 25 to 30 hours of flight time over a 6 to 8 week period. Cockpit noise in the jet trainer was stated to be 96-115 dB(A): the students received some hearing protection from their flight helmets. The results indicated no statistically discernible permanent threshold shift for the high frequencies measured. One might anticipate such a negative finding, considering the relatively short duration of protected noise exposure.

The authors' reported results can be of some positive use here. The subject sample comprised males, 21-28 years old, not screened for otological normality. All subjects gave thresholds for the lower frequencies; not all responded to the highest frequencies, even at the (unstated) maximum output of the audiometer. Consideration of the authors' data gives an upper frequency limit of 17.2 kHz for the hearing of these typical (not screened for normality) males.

Takeda et al. (1992)

The upper frequency limit of hearing was measured in 6105 normal ears of male and female subjects, ranging in age from 5 to 89 years. Potential subjects were excluded from the sample if there was a history of exposure to ototoxic medications or harmful levels of noise, or if conventional audiometry showed a hearing deficit of unknown origin. Ears were rejected if there were signs of otitis media or disease of the eardrum.

Pure-tone signals were swept from 50 kHz down to 0.5 kHz and presented to each subject by means of an earphone containing a condenser microphone driven as an output transducer. The output Sound Pressure Level was measured as 75 ± 10 dB across a restricted frequency range 0.5 to 25 kHz. Three to five sweeps were made for each ear, with the subject indicating when the swept tone was first heard. The upper limit was taken to be the median of the observed frequencies.

The values reported below in Table A1 represent 1423 ears of 869 males, and 2125 ears of 1314 females, all covering the age range 20- 69 years. Males and females exhibited similar values up to the age band 50-59 years. However, older males showed a narrower frequency range of hearing. This narrowing for Japanese males may be a manifestation of adventitious hearing loss by non-occupational noise exposure and deficiencies of general health, both known to affect males in the Western world.

Table A1
Values of the upper frequency limit of hearing by percentile, for otologically normal subjects in age bands of 10 years

Percentile	10%	25%	50%	75%	90%
Age (years)	Frequency (kHz)				
20-29	18.0	17.1	15.9	14.9	13.8
30-39	16.6	15.2	14.5	13.6	12.4
40-49	14.6	13.8	12.9	11.8	10.6
50-59	13.2	12.2	11.0	9.6	8.2
60-69	11.2	9.9	8.3	5.3	1.8

The absolute values of frequency may contain error associated with irregularities in the frequency response of the experimental equipment; the wide band of presentation level (75 ± 10 dB) almost certainly has introduced a small degree of random error between subjects. Despite these caveats, a trend is clear: high-frequency hearing ability is lost as the population ages.

Takeshima et al. (1994)

The threshold of hearing was determined for pure tones under free-field listening conditions, to provide data for a full-scale revision of International Standard ISO 226. The study was done in several stages, using a total of 69 otologically normal males and females aged 10-25 years. The full frequency range was covered, from 31.5 Hz to 20 kHz, but not all subjects heard all frequencies; for the VHF tones of interest here, 8 kHz and above, the subject numbers ranged from 18 to 37. The authors took the trouble to report the number of subjects responding to each frequency, at any level up to the maximum output (70 dB Sound Pressure Level) of their equipment, along with the total number of subjects employed. This precaution was used to explain the missing medians for the two highest test frequencies, 18 and 20 kHz. From this information, it was possible to estimate that the subjects' upper frequency limit of hearing was 17.4 kHz: half of the young listeners were able to hear tone of that frequency or higher, half heard only tones of lower frequency.

Sakamoto et al. (1998)

Hearing thresholds were determined over the frequency range 8-20 kHz for 65 normal subjects aged between 10 and 69 years. Over the conventional audiometric range, all subjects had Hearing Threshold Levels within a range considered normal-for-age. In addition, the subjects were screened for history of hearing difficulties, use of ototoxic medicines, and exposure to potentially harmful noise. The subjects were distributed in the decade age bands as below:

20-29 years	50 persons
30-39	20
40-49	9
50-59	27
60-69	10

The tones were presented by an earphone now accepted for VHF audiometry by International standard. The thresholds for each age band were presented as ‘means’ for each frequency, showing a considerable degree of compression of the thresholds at high frequencies near the audiometer’s maximum output. This erroneous trend resulted from truncation of the subjects responses; the ‘mean’ thresholds were calculated using only the data from subjects responding to the audiometers output, while ignoring the existence of subjects who did not hear the maximum signal presented. These researchers should have reported their results as median thresholds over all subjects.

Some of this work can be used for present purposes. The investigators gave the percentages of listeners (within each age band) responding to the VHF tones. These data have been processed for presentation here as the upper frequency limit of hearing, by age band. The highest frequency audible to 50% of the subjects with each age band is given in Table A2 below.

Table A2
Upper frequency limit of hearing, for otologically normal subjects in age bands of 10 years

Age band (years)	Frequency (kHz)
20-29	>20
30-30	>20
40-49	>20
50-59	16
60-69	13

These values seem high, but the maximum output from the earphone was a nominal 140 dB, somewhat higher than available to the subjects in other investigation.

Wiley et al. (1998)

As part of a large population study of hearing and ageing, hearing thresholds were reported for the ultra-high frequency range 9-20 kHz. All adults in a township in the US state of Wisconsin were invited to participate; a high percentage came forward for selection. The subjects, unscreened for hearing disorders, were separated into age bands: 48-59 years (sub-sample number n = 1233), 60-69 years (n = 1032), 70-79 years (n = 851), and 80-92 years (n = 281). In the conventional frequency range, the vast majority of the subjects had thresholds typical of age-associated hearing loss. A substantial portion of both male and female subjects did, however, report some degree of occupational noise exposure.

Pure-tone testing was performed covering the range 0.25-20 kHz, with signals of 9 kHz and higher presented by an earphone now specified for audiometric use (see BS ISO TR 389-5:1998). Threshold values were reported for right ears only, and only for those participants giving a response at individual frequencies; individuals with thresholds beyond the maximum output of the audiometer were excluded from the authors' analyses. This exclusion gave rise to quite drastic truncation of the reported measures of central tendency, seriously compromising the validity of the study. However, percentages of responders for each test frequency and for each sex were reported; these data were processed for presentation here as upper frequency limits of hearing for each age band possibly of present interest. The results indicated that:

	50% of males heard	50% of females heard
48-59 years	16.4 kHz	16.6 kHz
60-69	14.3	15.3
70-79	13.0	14.2

Recall that the subjects reported some degree of occupational noise exposure. This factor, reported mainly by males, seems not to have produced an effect in the youngest age group: the females with much less occupational noise and no military weaponsfire exhibited virtually the same upper limit. A gender difference is apparent for the older groups. This might be simply the widely-reported better hearing amongst older females. Alternatively, the difference might be a manifestation of noise-induced hearing damage in the males due to military service during World War Two or the Korean conflict. In any case, these values will serve as a representation of the upper frequency limit for typical (unscreened) males and females.

A3 THRESHOLD SHIFT WITH AGE

The items reviewed here deal mainly with threshold shift in the VHFs; some offer information on the upper limit of hearing as a side topic.

International Organization for Standardization (1961)

This Recommendation from ISO gives values of Sound Pressure Level for the normal binaural minimum audible field (MAF) for sinusoidal tones. A number of conditions are stated:

1. The source of sound is directly ahead of the listener.
2. The sound reaches the listener in the form of a free progressive plane wave.
3. The Sound Pressure Level is measured in the absence of the listener.
4. Listening is binaural.
5. The listeners are otologically normal persons in the age range 18 to 25 years inclusive. For the purposes of this ISO Recommendation, an "otologically normal person" is understood to be a person in a normal state of health who is free from all signs or symptoms of ear disease, and free from wax in the ear canals.

In addition to specifying the MAF for the 18-25 year old normals, coefficients are given which permit the calculation of what might be called 'threshold shift' due to age. The results are given in Table A3 below. The first row of values, for persons 18-25 years of age, contains all zeroes; this convention will be seen in all following tables, to remind the reader of the baseline against which all shifts are measured. The ages 35, 45, 55 have been chosen to represent the age decades 30-39 etc. used in other reviews of this Appendix.

Table A3
Shift of threshold with age, by decade

Frequency (kHz)	8	9	10	11	12	13	14	15
Age (yr)	Threshold shift (dB)							
18-25	0	0	0	0	0	0	0	0
35	4.5	5.5	6.5	8.0	9.5	11.5	14.5	19.0
45	12.0	13.5	16.5	20.0	24.0	29.5	37.0	48.0
55	15.5	17.5	21.0	25.5	30.5	37.5	47.0	61.5

Later versions of this document (ISO 226: 1987 and its British manifestation BS 3383: 1988) are not so useful for present purposes. The MAF is specified only up to 12.5 kHz, and there is no facility for calculating the shift of MAF with increasing age.

Rosen, Plester, El-Mofty, Rosen (1964)

These researchers investigated hearing thresholds as a function of age, for the frequencies 12 to 24 kHz. More than 2 900 subjects, comprising roughly equal numbers of males and females covering an age range from 10 to more than 70 years, were tested in Africa, Europe and North America. No information was given describing subject selection in New York, Cairo, Düsseldorf and a remote area of Sudan, so it must be assumed that the participants were members of the typical population, rather than otologically normal.
The threshold Sound Pressure Levels were reported by frequency and by age bands: 10-19, 20-29, 30-39, 40-49, 50-59, 50-69 and 70-79 years. The Sudanese data will not be considered here: their ages could only be estimated. Also, the data from the youngest group will not be included here.

The authors report the percentage of subjects in the urban centres who responded to signals presented by a quasi-free-field technique, with a loudspeaker supported at a constant, known distance from the test ear. These data have processed for presentation here as the median upper frequency limit of hearing, for the groups of more than 300 urban subjects in each age band:

20-29 years	18.5 kHz
30-39	16.5
40-49	15.0
50-59	13.0

Age-associated hearing loss is usually thought of as decline of sensitivity in the high audiometric frequencies. As seen here, the same phenomenon is manifest as a decrease in the highest frequency audible.

The median thresholds were reported for each subject sample, by age group. The given Sound Pressure Levels are of no direct interest here, being dependent upon presentation equipment and calibration technique. However, as each sub-sample was tested as a separate group, the shift of threshold with age can be reported by frequency, using the 20-29 year old subjects as a baseline. These threshold shifts are given in Table A4 below.

Table A4
Shift of threshold with age, by decade, for three urban samples

Frequency (kHz)		12	14	16
Location of sample	Age range (years)	Threshold shift (dB)		
New York	20-29	0	0	0
	30-39	12.0	15.4	29.7
	40-49	26.9	47.4	*
	50-59	54.1	*	*
Düsseldorf	20-29	0	0	0
	30-39	8.5	20.5	23.0
	40-49	32.9	48.3	*
	50-59	52.1	*	*
Cairo	20-29	0	0	0
	30-39	16.0	26.6	33.7
	40-49	29.9	51.0	*
	50-59	59.4	*	*

* insufficient responses to determine median for subject group

Sataloff, Vassallo, Menduke (1967)

These investigators sought high-frequency hearing thresholds in paper mill workers with existing noise-induced hearing losses, to be contrasted with thresholds from 39 male office staff with no noise exposure or otological problems. The control group comprised 8 individuals in the age range 20-29 years, 21 in the 30-39 year band, and 10 in the 40-49 year band. Right-left average hearing thresholds at 10, 12 and 14 kHz were listed for all subjects; this permitted verification that medians were not influenced by truncation of the audiometer output through the insert earphone.

Threshold shifts for the 39 control subjects are given in Table A5. The value for each frequency and age group is relative to the threshold given for the band 20-29 years.

Table A5
Threshold shifts (dB) by age band,
for the paper mill controls

Frequency (kHz)	10	12	14
Age range (years)	Threshold shift (dB)		
20-29	0	0	0
30-39	0	11	12
40-49	8	27	23

Northern et al. (1972)

The results of a high-frequency hearing survey are reported. Professional persons attending a speech and hearing conference were screened by otological examination. A limited number of participants admitted to prolonged noise exposure; the thresholds given by these individuals were not substantially different from the non-exposed subjects, so all subjects were included in the data presentation.

The subject sample was nearly evenly split between males and females, but weighted more towards younger persons:

Age range (years)	Number
20 - 29	117
30 - 39	63
40 - 49	37
50 - 58	16

Each subject tracked his or her thresholds for the frequencies 8 to 18 kHz in one randomly chosen ear, with the test tones presented by an insert earphone. The authors give mean and median Sound Pressure Levels only for those subjects giving a response at each frequency, ignoring any thresholds beyond the output range of the audiometer. Despite this serious shortcoming, sufficient information was given to indicate which medians were unreliable due to truncation. The trustworthy data were processed to give threshold shifts at a number of test frequencies, for each age group; these values are given below:

Table A6
Threshold shift (dB) for the older subject groups, in relation to the 20-29 year old group

Frequency (kHz)	8	9	10	11	12	13	14	15	16
Age (years)	Threshold shift (dB)								
20-29	0	0	0	0	0	0	0	0	0
30-39	8	9	9	13	15.5	19	22	21	26.5
40-49	14.5	15	22.5	25.5	29.5	*	*	*	*
50-58	29.5	33	36.5	38.5	48	43.5	46	*	*

* insufficient responses to determine median for subject group

These shifts show two common-sense trends. For any given frequency, threshold shift increases with age. For each of the older subject groups, the shift becomes greater with increasing frequency.

As well as the threshold Sound Pressure Levels, the authors also reported the percentage of subjects within each age band who responded at each frequency. These data enabled determination of the upper frequency limit of hearing for each age band:

20-29 years	>17.0 kHz
30-39	16.1
40-49	12.7
50-59	14.2

Note the anomalous entry for the 40-49 year band, which contains a majority of males who were of military service age during the Second World War. The distorted pattern of the upper limits (and of the thresholds of Table A6) may be a result of hazardous noise exposure considered usual for males of that age.

Osterhammel, Osterhammel (1979, 1985)

These investigators used their quasi-free field high-frequency audiometer (described in Osterhammel et al., 1977 and Osterhammel, 1978) to determine thresholds by age band and sex. Before testing, all potential subjects were questioned regarding ear disease, noise exposure, head trauma, hereditary conditions involving hearing deficits, and hormonal diseases. Persons over 50 years old were also questioned about heart and vascular disease, and had their blood pressure determined. Only those with negative histories, normal eardrums and normal middle ear test results were accepted as subjects. In all, 286 were tested: 152 females and 134 males ranging in age from 10 years to over 70 years.

The absolute threshold values reported by the authors were used to calculate change of threshold level with increasing age, for both sexes. These derived data is given in Table A7 where the 20-29 year-olds form the threshold baseline; changes (in dB) are given for males and females. A fundamental trend may be seen in the data: thresholds at any frequency increase (become worse) with increasing age, with the increase accelerating for higher frequencies.

Table A7
Change of threshold at individual frequencies; absolute thresholds for males and females in the 20-29 year age group were not significantly different

Frequency (kHz)	8	10	12	14	16	18	20
Age band (years)	Threshold shift (dB)						
males							
20-29	0	0	0	0	0	0	0
30-39	5	5	5	19	20	14	8
40-49	11	13	15	44	38	*	*
50-59	29	36	43	59	*	*	*
60-69	35	39	53	68	*	*	*
≥ 70	59	62	65	*	*	*	*
females							
20-29	0	0	0	0	0	0	0
30-39	3	8	6	13	20	15	5
40-49	10	13	16	36	35	20	*
50-59	20	35	44	54	45	*	*
60-69	33	55	66	*	*	*	*
≥ 70	63	73	71	*	*	*	*

* insufficient responses to determine median

The researchers also report, for each age band, the percentage of subjects responding to the high-frequency stimuli, at any presentation level up to the maximum output of their audiometer. These data have been analysed for presentation here in Table A8 as the upper frequency limit of hearing, as also seen in Takeda S *et al*. (1992 a and b).

Table A8
Median upper frequencies heard by males and females, by age group

Age range (years)	Upper frequency limit of hearing (kHz)	
	50% of males would hear:	50% of females would hear:
10-19	>20	>20
20-29	>20	>20
30-39	20.0	20.0
40-49	17.2	18.1
50-59	15.6	16.3
60-69	14.5	13.3
≥ 70	12.6	12.0

Ribári, Kiss (1983)

These investigators advocate the use of high-frequency audiometry for the early detection of occupational hearing loss. Using a high-frequency output transducer located 70 mm from the ear canal of each testee, they determined the hearing thresholds for the frequencies 8 to 20 kHz in 50 male workers with known occupational noise exposure. Unfortunately, the authors chose to report their threshold data grouped by years of noise exposure at work, but without consideration of the age of individual workers. This confounding of variables could have been avoided, as these researchers had information on the marked deterioration of high-frequency thresholds through natural ageing.

High-tone hearing thresholds were determined for 50 healthy subjects judged to have normal hearing, according to thresholds given by conventional audiometry. The absolute thresholds were presented for mixed-sex groups of 10 subjects in ten-year age bands. These thresholds are of little use here, but the change of threshold, relative to the youngest age group (20-29 years), is worth considering; these data are given in Table A9 below. Scanning down the table column devoted to each frequency, the values increase more-or-less smoothly with age. Going across each age row, the difference-values increase at first, then decrease for the highest frequencies. Without access to the original data, this unexpected trend cannot be explained. However, such ‘roll-over’ trends have been seen in the results of other researchers, in all cases resulting from ignoring non-responders who were not able to hear even maximum output signals. The authors do not give sufficient information to test this idea.

Herbertz (1983)

Hearing thresholds were obtained from 57 visitors to the Hannover Fair. These persons, presumably not highly screened for normality, gave thresholds for the conventional audiometric range, but were also tested at 10, 12.5, 16, 20, 25, 31.5 and 40 kHz by a quasi-free-field technique. The results, thresholds and threshold shift with increasing age, seem to fly in the face of all data published before and since.

The very high frequency and ultrasonic tones were generated by a piezoelectric resonator with attached horn, then broadcast through air to the test ear 10 cm away. The subjects gave responses

Table A9
Mean change of thresholds with age, for mixed-sex groups of normal subjects; relative to the hearing thresholds of the youngest group (20-29 years)

Frequency, (kHz)	8	9	10	11	12	13	14	15	16	17	18	19	20
Age (years)	Threshold shift (dB)												
20 - 29	0	0	0	0	0	0	0	0	0	0	0	0	0
30 - 39	10	10	12	10	17	17	21	19	20	23	17	10	13
40 - 49	18	17	22	15	31	33	28	30	35	33	32	30	35*
50 - 59	33	34	40	40	50	48	53	missing	52	48	42	40*	†
60 -	43	48	55	60	70	65	67	72	72*	†	†	†	†

* range truncated due to restriction of maximum output from the audiometer
† no value reported, beyond maximum output from the audiometer

for signals beyond 20 kHz, the widely-accepted upper frequency limit of human hearing. The median thresholds, for all subjects regardless of age, were:

Frequency (kHz)	Threshold (dB)
20	102
25	124
31.5	136
40	142

In addition, the influence of age was derived from the threshold data for all frequencies, for all subjects. Up to 16 kHz, there was a smooth function of dB threshold increase per year, showing 1 kHz to be virtually unaffected by age (zero dB per year of increasing age), while 16 kHz showed threshold change of more than 1 dB per year. This seems quite straightforward. However, the trend reversed for the higher frequencies, eventually indicating a constant threshold for 40 kHz over the age range 17 to 59 years. This is difficult to credit.

The investigator made no effort to reconcile his own anomalous results with data from the world literature. At least two possibilities should have been considered: the subjects gave responses to some extraneous acoustic signal, for instance a transient at signal-on-signal-off; or the subjects gave responses to some stimulus completely unconnected with the sensation of hearing, such as local heating in the ear canal. It seems safe to put aside the results from Herbertz, at least until some other worker has replicated his findings.

Grzesik, Pluta (1983, 1986a)

These researchers undertook a programme of hearing tests amongst ultrasonic workers. To identify noise-induced hearing loss in the workers, they obtained thresholds in the VHF range for a non-noise-exposed control group, comprising 80 males and 109 females aged 17-49 years. Threshold were determined for the controls using a hybrid microphone-for-output and insert transducer. As before, the reported VHF thresholds have been processed to yield threshold shifts for the older groups, relative to the values given by the subjects aged 20-29 years. The shifts at each frequency are given below:

Table A10
Mean threshold shifts for the control subjects, aged 20-49 years

Frequency (kHz)	10	11	12	13	14	15
Age (years)	Threshold shift (dB)					
20-29	0	0	0	0	0	0
30-39	4	6	7	8	10	14
40-49	12	17	22	*	*	*

* mean not calculated, missing responses for older subjects

The absence of data above 15 kHz is a consequence of insufficient responses from the older groups to allow calculation of mean threshold levels, or threshold shifts at the mean. The authors did, however, give the percentage of subjects responding to each frequency, in each age group. An upper frequency limit of audible sound has been derived for each age band:

age	50% able to hear upper frequency of
20-29 years	18.3 kHz
30-39	16.9
40-49	15.2

These data show the expected trend, an inverse relation between subject age and upper frequency limit of hearing.

Stelmachowicz, Beauchaine, Kalberer, Jesteadt (1989)

Using a prototype high-frequency audiometer, hearing thresholds over the range 8 to 20 kHz were determined for 240 subjects ranging in age from 10 to 59 years. The only data applicable for present purposes are thresholds from 40 males and 40 females aged 20 to 59 years. All subjects of this sub-sample were screened by conventional audiometry (0.25-8 kHz) for hearing thresholds within the range considered normal for age and sex; normal middle ear function, and negative history of noise exposure and ototoxic medication were also verified. The high-frequency signals were presented, to one ear for each subject, by means of a suitable transducer coupled to the ear by a long tube ending with a canal insert.

The raw threshold means for each frequency and age group have been processed further to give threshold shift relative to the 20-29 year old group; these shifts are given in Table A11. The authors commented that all listeners responded to some aspect of the stimuli at very high output levels, but many reported “atonal percepts” at the frequency and level extremes of the audiometer. The pattern of results suggested a ‘ceiling effect’ or truncation imposed by equipment limitations; in the shifts of the Table, such truncations are indicated by the asterisk. The results for 19 and 20 kHz are quite obviously subject to this admitted ‘ceiling effect’ and have not been included in the Table.

In general, the trends are satisfying. Within any age band, the threshold shift become larger as the frequency increases. For any one frequency, the threshold shift becomes greater as the subjects become older. Both of these trends mirror the behaviour of age-associated hearing loss in the lower, conventional audiometric frequencies.

Löppönen, Sorri, Bloigu (1991)

A study was undertaken to determine VHF thresholds by electric bone-conduction audiometry. In all, 208 male and female subjects were tested, without screening tests for admission to the study population. The main aim of the study is of no interest here, but these typical subjects did give VHF air-conduction thresholds to peg the bone-conduction data to SPL values. The median thresholds by air have been manipulated to give change of threshold by age band, referenced to the thresholds for subjects near 20 years of age; see Table A12.

Hallmo, Sundby, Mair (1994)

These researchers reported on extra high-frequency thresholds by bone conduction. As a by-product of their study, air-conduction thresholds were given for their otologically normal subjects, 100 males and 105 females, separated into the age bands 18-24, 30-39, 40-49, 50-59,

Table A11
Threshold shifts, relative to the 20-29 year old subjects, at each frequency.

Frequency (kHz)	8	9	10	11	12	13	14	15	16	17	18
Age (years)	Threshold shift (dB)										
20-29	0	0	0	0	0	0	0	0	0	0	0
30-39	2	2	3	4	4	4	4	10	13	15	13
40-49	8	13	11	14	14	18	24	28	28	22	*
50-59	29	34	41	45	51	54	59	56	48	*	*

* threshold shift subject to truncation by limited maximum output of audiometer.

Table A12
Threshold shift by sex and age band for typical older subjects

Frequency (kHz)	8	10	12	14	16	18
Sex, age range (yr)	Threshold shift (dB)					
males						
19-26	0	0	0	0	0	0
40-41	5	10	25	50	*	*
60-61	42	65	70	*	*	*
females						
18-27	0	0	0	0	0	0
37-43	5	5	15	38	40	*
60-61	33	48	60	*	*	*

* not measurable, insufficient responses to determine median

and 60-69 years. As before, the absolute thresholds have been processed to give threshold shift be age band; these shifts (relative to the youngest age band) are presented in Table A13 for the male and female subjects. The original data were reported as median thresholds determined with a 5 dB Hearing Level step; this rough quantization may be seen in the threshold shift data of the Table.

The median thresholds, and consequently the threshold shifts, are not well-behaved at the extremes of age and/or frequency; values do not exhibit the expected increase with either variable. An implausible ‘compression’ is obvious in the medians presented by the authors; this compression, always associated with the maximum output of the audiometer, produces a ‘roll-over’ in the threshold shift values (in parentheses). Such aberrant median values are consistent with counting only responders, although the authors specifically deny this statistical mistake. In any case, the authors offer no explanation of the compression found in their results, seen here as a ‘roll-over’ in the threshold shifts. The values in parentheses must be regarded as suspect.

A4 SUMMARY VALUES

This section brings together, perhaps for the first time, the available data on age-associated hearing loss for VHF tones. Table A14 gives the upper frequency limits of hearing, by age band, as reported by a number of investigators. The Table entries represent the median reported in, or derived from each source; the subject numbers represented by each entry vary from tens to hundreds. The estimate of central tendency for each age band is a sort of ‘median of medians’, giving each study an equal weight regardless of the actual number of subjects tested. Note the slight irregularity for the 40-49 and 50-59 year age bands, possibly attributable to wartime noise exposure in the male subjects. Combination of the data for these two age bands permitted a smoothed estimate.

A similar approach is adopted for threshold shift with age. Table A15 gives the shifts derived from reports by a number of investigators, for the frequencies 8-16 kHz. Each Part of the Table gives the observed shifts for a stated age band, relative to the youngest group, aged 20-29 years. For each age band, the bottom row presents an estimate of central tendency, giving each study an equal weight regardless of the actual number of subjects tested (again tens to hundreds).

The summary rows of Table A15, Parts a to d, have been brought together below to facilitate examination of the trends over age and frequency. Taking the age band 20-29 years as a baseline, one may see that threshold shift increases with age for every frequency. It is gratifying

Frequency (kHz)	8	9	10	11	12	13	14	15	16
Age band (yr)					Threshold shift (dB)				
20-29	0	0	0	0	0	0	0	0	0
30-39	5	7	7	10	10	11.5	15.4	19	21.5
40-49	10	15	13	20	26.9	33	44	48	38
50-59	24.5	29	35.5	37	50	51	56.5	—	—
60-69	35	48	55	60	70	—	—	—	—

to see that the threshold shift values for 8 kHz are in very good agreement with values given in International standards. Until a controlled survey is conducted to document VHF threshold shifts with age for populations of otologically normal males and females, the summary data here may serve as a stopgap, to represent the trends of shifts with increasing age and frequency.

Table A13
Threshold shifts, relative to the 18-24 years old males or females, at each frequency; 'roll-over' values in parentheses are not to be trusted

Frequency (kHz)	8	9	10	11	12	13	14	15	16	17	18
Sex, age (years)	Threshold shift (dB)										
males											
18-24	0	0	0	0	0	0	0	0	0	0	0
30-39	5	5	10	10	10	15	20	30	35	30	(5)
40-49	10	15	15	20	30	40	50	50	(45)	(35)	(10)
50-59	15	25	27.5	35	45	60	60	(60)	(55)	(40)	—
60-69	40	52.5	55	70	75	—	—	—	—	—	—
females											
18-24	0	0	0	0	0	0	0	0	0	0	0
30-39	5	10	10	10	10	10	10	20	20	25	—
40-49	10	15	15	20	30	40	47.5	52.5	40	—	—
50-59	15	20	20	30	50	55	65	(62.5)	(45)	(30)	—
60-69	35	45	55	60	72.5	75	(70)	(65)	(45)	(35)	(15)

Table A14
Summary: Upper frequency limit of hearing by age band

Age band (years)	20-29	30-39	40-49	50-59	60-69	70-79
Source:	Frequency (kHz)					
Rosen *et al.* (1964)	18.5	16.5	15.0	13.0		
Mason (1967)	17.5	15.5	13.5			
Northern *et al.* (1972)	>17.0	16.1	12.7	14.2		
Robertson, Williams (1975)	17.2					
Osterhammel *et al.* (1979, 1985)						
male	>20	20.0	17.2	15.6	14.5	12.6
female	>20	20.0	18.1	16.3	13.3	12.0
Grzesik, Pluta (1983, 1986a)	18.3	16.9	15.2			
Takeda *et al.* (1992)	15.9	14.5	12.9	11.0	8.3	
Takeshima *et al.* (1994)	17.4					
Wiley *et al.* (1998)						
male				16.4	14.3	13.0
female				16.6	15.3	14.2
Sakamoto *et al.* (1998)	>20	>20	>20	16	13	
Estimate of central tendency	17.9	16.7	15.1	15.8	13.8	12.8
Smoothed estimate	17.9	16.7	15.7	14.8	13.8	12.8

Table A15 Part a
Threshold shift in subjects aged 30-39 years, relative to the youngest age band

Frequency (kHz)		8	9	10	11	12	13	14	15	16
Source:		Threshold shift (dB) re 20-29 year age band								
ISO (1961)		4.5	5.5	6.5	8.0	9.5	11.5	14.5	19.0	
Rosen *et al.* (1964)	New York					12.0		15.4		29.7
	Düsseldorf					8.5		20.5		23.0
	Cairo					16.0		26.6		33.7
Sataloff *et al.* (1967)				0		11		12		
Northern *et al.* (1972)		8	9	9	13	15.5	19	22	21	26.5
Osterhammell *et al.* (1979)	male	5		5		5		19		20
	female	3		8		6		13		20
Ribari, Kiss (1983)		10	10	12	10	17	17	21	19	20
Grzesik, Pluta (1986a)				4	6	7	8	10	14	
Stelmachowicz *et al.* (1989)		2	2	3	4	4	4	4	10	13
Hallmo *et al.* (1994)	males	5	5	10	10	10	15	20	30	35
	females	5	10	10	10	10	10	10	20	20
	Median	5	7	7	10	10	11.5	15.4	19	21.5

Table A15 Part b
Threshold shift in subjects aged 40-49 years, relative to the youngest age band

Frequency (kHz)		8	9	10	11	12	13	14	15	16
Source:		Threshold shift (dB) re 20-29 year age band								
ISO (1961)		12.0	13.5	16.5	20.0	24.0	29.5	37.0	48.0	
Rosen *et al.* (1964)	New York					26.9		47.4		*
	Düsseldorf					32.9		48.3		*
	Cairo					29.9		51.0		*
Sataloff *et al.* (1967)				8		27		23		
Northern *et al.* (1972)		14.5	15	22.5	25.5	29.5	*	*	*	*
Osterhammell *et al.* (1979)	male	11		13		15		44		38
	female	10		13		16		36		35
Ribari, Kiss (1983)		18	17	22	15	31	33	28	30	35
Grzesik, Pluta (1986a)				12	17	22				
Stelmachowicz *et al.* (1989)		8	13	11	14	14	18	24	28	28
Löppönen *et al.* (1991)	males	5		10		25		50		
	females	5		5		15		38		40
Hallmo *et al.* (1994)	males	10	15	15	20	30	40	50	50	(45)
	females	10	15	15	20	30	40	47.5	52.5	40
	Median	10	15	13	20	26.9	33	44	48	38

* insufficient subject numbers to calculate median; (roll-over) values untrustworthy

Table A15 Part c
Threshold shift in subjects aged 50-59 years, relative to the youngest age band

Frequency (kHz)		8	9	10	11	12	13	14	15	16
Source:		Threshold shift (dB) re 20-29 year age band								
ISO (1961)		15.5	17.5	21.0	25.5	30.5	37.5	47.0	61.5	
Rosen *et al.* (1964)	New York					54.1		*		*
	Düsseldorf					52.1		*		*
	Cairo					59.4		*		*
Northern *et al.* (1972)		29.5	33	36.5	38.5	48	43.5	46	*	*
Osterhammell *et al.* (1979)	male	29		36		43		59		—
	female	20		35		44		54		45
Ribari, Kiss (1983)		33	34	40	40	50	48	53	missing	52
Stelmachowicz *et al.* (1989)		29	34	41	45	51	54	59	56	48
Hallmo *et al.* (1994)	males	15	25	27.5	35	45	60	60	(60)	(55)
	females	15	20	20	30	50	55	65	(62.5)	(45)
	Median	24.5	29	35.5	37	50	51	56.5	—	—

* insufficient subject numbers to calculate median; (roll-over) values untrustworthy

Table A15 Part d
Threshold shift in subjects aged 60-69 years, relative to the youngest age band

Frequency (kHz)		8	9	10	11	12	13	14	15	16
Source:		Threshold shift (dB) re 20-29 year age band								
Osterhammell *et al.* (1979)	male	35		39		53		68		—
	female	33		55		66		—		—
Ribari, Kiss (1983)		43	48	55	60	70	65	67	72	72*
Löppönen *et al.* (1991)	males	42		65		70				
	females	33		48		60				
Hallmo *et al.* (1994)	males	40	52.5	55	70	75	—	—	—	—
	females	35	45	55	60	72.5	75	(70)	(65)	(45)
	Median	35	48	55	60	70	—	—	—	—

* insufficient subject numbers to calculate median; (roll-over) values untrustworthy

Table A16
Summary: Threshold shift by age band, relative to persons 20-29 years old

Frequency (kHz)	8	9	10	11	12	13	14	15	16
Age band (years)	Threshold shift (dB)								
20-29	0	0	0	0	0	0	0	0	0
30-39	5	7	7	10	10	11.5	15.4	19	21.5
40-49	10	15	13	20	26.9	33	44	48	38
50-59	24.5	29	35.5	37	50	51	56.5	—	—
60-69	35	48	55	60	70	—	—	—	—

Printed and published by the Health and Safety Executive
C1 04/01

HSE BOOKS

MAIL ORDER
HSE priced and free
publications are
available from:
HSE Books
PO Box 1999
Sudbury
Suffolk CO10 2WA
Tel: 01787 881165
Fax: 01787 313995
Website: www.hsebooks.co.uk

RETAIL
HSE priced publications
are available from booksellers

HEALTH AND SAFETY INFORMATION
HSE InfoLine
Tel: 08701 545500
Fax: 02920 859260
e-mail: hseinformationservices@natbrit.com
or write to:
HSE Information Services
Caerphilly Business Park
Caerphilly CF83 3GG

HSE website: www.hse.gov.uk

CRR 343

£15.00

ISBN 0-7176-2019-0

9 780717 620197