MILITARY AVIATION NOISE
Noise-induced hearing impairment and noise protection

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OU LU 2004
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Academic Dissertation to be presented with the assent of the Faculty of Medicine, University of Oulu, for public discussion in the Auditorium 101 A of the Faculty of Medicine (Aapistie 5 A), on September 3rd, 2004, at 12 noon.

OULUN YLIOPISTO, OULU 2004
Kuronen, Pentti, Military aviation noise. Noise-induced hearing impairment and noise protection
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Oulu, Finland

Abstract
This research on military aviation noise was conducted because the personnel working with military aircraft were concerned about noise induced hearing damage. In addition, comprehensive data on hearing impairments and occupational exposure of military pilots in the Finnish Air Force was not available. Moreover, data on the effects of overflight noise of military jets was necessary for the evaluation of noise induced hearing deteriorations of members of the public who might be exposed accidentally for the low-level jets' overflights.

The averaged noise exposure levels of pilots varied during a flight from 97 dB(A) to 106 dB(A) in the cockpit and from 83 dB(A) to 100 dB(A) at the entrance of the ear canal. Radio noise was 4–10 dB higher than background noise inside the helmet. The attenuation provided by air crew helmets varied from 10 to 21 dB(A) in the laboratory, and was at the same level during real flights. The attenuation measured in the laboratory and in working conditions was about 30 dB(A) for earmuffs. An active noise cancellation (ANC) device decreased averaged noise exposure ($L_{Aeq8min}$) 4–8 dB over the noise attenuation of the same helmets when the ANC system was off.

The noise of overflights by military jets were measured and the noise levels were lower than those known to cause the permanent threshold shifts. However, noise induced hearing damages might be possible in certain conditions.

In order to assess the hearing loss risk of pilots, hearing thresholds were measured before and after one flight using both conventional and extended high frequency (EHF) audiometry. Minor temporary threshold shifts (TTS) were revealed. The risk of noise-induced damage at the studied exposure levels is, in all probability, rather small.

A novel NoiseScan data management system proved to be an interesting tool in assessment of the risk of developing hearing impairment on the basis of known risk factors. Due to the small number of risk factors, the hearing of pilots was shown to be at considerably less risk than that of industrial workers in Finland.

Keywords: acoustic trauma, audiometry, extended high-frequency audiometry, military aviation, noise, noise induced hearing impairment, noise protection, permanent threshold shift, temporary threshold shift
Acknowledgements

The present study was carried out at the Department of Otorhinolaryngology, Oulu University Hospital, and in the Finnish Air Force. The study was started in the early 1980s; however, it was mainly carried out from the mid-1990s onward.

First, I would like to thank Professor Martti Sorri, M.D., my supervisor at the Department of Otorhinolaryngology, University of Oulu. He patiently supported and continuously encouraged me. He always had time to advise and teach me in audiology and to assist me in my work on the details of this study during the years. His support was essential. I am also grateful to Professor Kalevi Jokinen, M.D., Head of the Department of Otorhinolaryngology, University of Oulu, for his interested and supportive attitude. He also offered the facilities and personnel of his clinic to help me carry out this study.

I owe my special and warmest thanks to Docent Rauno Pääkkönen, Dr. Tech., from Tampere Regional Institute of Occupational Health. He was my most important cooperator during my work on the study. Without his support, which went beyond my expectations, and profound knowledge of noise measurement and other aspects of noise, this study would not have been possible. Besides aviation noise, he has also been specialist in measurements conducted by the Finnish Defence Forces of noise generated by firearms of all calibers. I am also indebted to Colonel Seppo Savolainen (M.C.), Head of the Department of Otorhinolaryngology of the Central Military Hospital. He is a very experienced researcher, and his advice and support were most important.

I am grateful to Professor Emeritus Juhani Kärjä for his great support and plentiful advice he provided during the audiological measurements and exposure assessment of pilots in the initial phase of the study. At that time Professor Kärjä was Head of the Department of Otorhinolaryngology at Kuopio University Hospital. I am also very grateful to Colonel Juhani Also (M.C.), who was my superior and the Chief Flight Surgeon of the Finnish Air Force until his retirement in 1990. He is an experienced specialist in otorhinolaryngology and gave valuable support to me in my study. I also wish to thank Lieutenant-General Kimmo Koskenvuo (M.C.), who was the Surgeon General of The Finnish Defence Forces in 1978–1996 and created the spirit of research work in the field of military medicine.

I would like to express my warmest gratitude to my co-authors, Professor Jukka Starck, Dr. Tech., and Docent Esko Toppila, Ph.D., from the Finnish Institute of
Occupational Health. Their support was most important during the study. I also wish to thank Mr. Arto Muhli, biostatistician, for his important and valuable work during the study.

I wish to thank the official reviewers of this work, Professor Einar Laukli, Dr. Tech., University Hospital of Tromsø, Norway, and Professor Jukka Ylikoski, M.D., University Of Helsinki, for their constructive and profound criticism and proposals which improved this study significantly.

I am grateful to Keith Kosola, B.Sc., and Professor Malcolm Richardson for their important support in revising the language of this study. I express my best thanks to Mr. Tapio Kakko, chief translator at the Finnish Air Force Headquarters, who did excellent work in revising the text especially in vocabulary related to special aviation language.

My special and warmest thanks go to my closest workmates at the Finnish Air Force Headquarters, Captain Taisto Puhakka and Ms. Soili Samanen. Their support in all kinds of practical arrangements during the work was extremely important, and I will always remember them as members of the best working group I have ever had. I also wish to thank Captain (Tech.) Ossi Aatsalo, who provided support and information in all kinds of matters concerning flight gear and measurements in flight conditions.

The Finnish Air Force and the General Headquarters of the Finnish Defence Forces supported me in many ways during the years. The positive environment for research work has been essential to success in this type of study. Commanders-in-Chief of the Finnish Air Force, Lieutenant-General Matti Ahola (1995–1998) and Lieutenant-General Jouni Pystynen (1998–2004) supported aviation medicine research and this study to a great extent. I am very grateful for that.

Finally, my warmest and most loving thanks go to my family; my wife Kirsti for her encouragement during the busy years, and my son Lauri, who has been a real joy for both of us.

Palokka, August 2004

Pentti Kuronen
## Abbreviations

<table>
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<th>Description</th>
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<tbody>
<tr>
<td>AAT</td>
<td>acute acoustic trauma</td>
</tr>
<tr>
<td>AB</td>
<td>afterburner (of a fighter aircraft, producing more thrust)</td>
</tr>
<tr>
<td>EHF</td>
<td>extended high-frequency</td>
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<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>FiAF</td>
<td>Finnish Air Force</td>
</tr>
<tr>
<td>HL</td>
<td>hearing level</td>
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<tr>
<td>NIHL</td>
<td>noise-induced hearing loss</td>
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<tr>
<td>PTS</td>
<td>permanent threshold shift</td>
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<tr>
<td>SPL</td>
<td>sound pressure level</td>
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<tr>
<td>TTS</td>
<td>temporary threshold shift</td>
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List of original articles

This thesis is based on the following communications, which will be referred to in the text by their Roman numerals.


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1 Introduction

Noise has been recognised as a problem, both environmentally and operationally, since the earlier days of aviation. The inherent noise environment of military aviation consists of several types of continuous, transient, and partly impulsive noise. Noise exposure can result in hearing impairment in the form of a temporary threshold shift (TTS) or a permanent threshold shift (PTS) among pilots. These two phenomena possess specific characteristics whose mechanisms in the sensory system remain as yet partly unknown.

Actual noise exposure, protection levels, acute and long-term effects of aviation noise on pilots’ and maintenance technicians’ hearing levels were not very well known in the Finnish Air Force (FiAF). Also, the personnel were worried about their noisy working environment and possible hearing impairment caused by military aviation noise. Therefore, this research programme was conducted on these topics.

The present study was considered to be of importance because, until recently, there have not been many studies of military aviation noise and hearing impairment. TTS and extended high-frequency audiometry (EHF) were not available on this topic before this research. Also, new data was found concerning acute acoustic trauma (AAT) after overflights by military jets. On the other hand, after earlier studies, there have been changes in noise exposure conditions and protection devices. Besides, a new database programme was available for comparing the risk of a PTS and pilots with other professions in Finland. After all, the annual examinations of military pilots are carried out at the same hospital, so consequently, the data of the audiometric results and other risk factors of FiAF pilots were easily and reliably available.
2 Review of the literature

2.1 Physics of sound

This research was intended to provide basic information on aviation noise effects on the human being for the Finnish Air Force (FiAF). Therefore, some concepts of sound and noise are included in this chapter.

Sound is the propagation of pressure waves radiating from a vibrating source through an elastic medium, like a liquid, gas or a solid medium. Sound waves travel in straight lines in all direction from the source, involving a succession of compressions and rarefactions of the elastic medium and decreasing in intensity at a rate inversely proportional to the square of the distance from their source. The waves are characterised by the amplitude of sound pressure changes, their frequency, and the velocity of propagation. One complete period consists of one compression and one rarefaction. The speed of sound (c), frequency (f) and wavelength (\(\lambda\)) are related according to the equation:

\[ c = f \times \lambda \]

A simple type of sound wave is called a pure tone. The source of such a sound, like a string, moves harmonically and produces a sinusoidal pressure cycle that is completely defined in terms of a single frequency and pressure amplitude at a given time. The number of times such a cycle occurs in a given time is called frequency. One cycle per second (Cps) is called hertz (Hz = 1/sec). Pure tones do not occur in nature, and environmental noise, for example, is always a combination of many frequencies.

2.2 Definitions of sound and noise

Physically there is no distinction between sound and noise. Every vibration of an elastic medium which a healthy ear can perceive is called sound. Noise is a class of sounds that are considered undesirable. Noise may cause harmful effects on the health and well-being...
of individuals and populations. A typical harmful health effect is noise-induced hearing loss (NIHL). On the other hand, it is not possible to define noise exclusively on the basis of the physical parameters of sound. It is common to define noise operationally as audible acoustic energy that may affect the physiological and psychological well-being of people (Berglund & Lindvall 1995a).

The principal features of sound that we need to measure are frequency and intensity. Both are measured with a technique called scaling. In audiology, an octave scale is often used for frequencies. The audible frequency range is technically covered by 10 octave bands. The octave scale is logarithmic, and each octave increase corresponds to a doubling of the previous frequency. The octave band level at a particular centre frequency is the level of the sound measured when all the acoustic energy outside this band is excluded. One-third octave band filters, which are widely used, e.g., for noise assessment purposes, subdivide each octave interval into three parts and provide a more detailed description of the sound spectrum (ISO 266 1975). Sound intensity is also measured on a logarithmic ratio scale in decibels.

2.3 Acoustics

2.3.1 Hearing level, HL

The frequencies between 0.2–20 kHz are normally considered to be audible for younger listeners with unimpaired hearing. The important reference (zero) level in audiology is based on normally hearing young subjects’ hearing thresholds. Several standards have been used, but currently the reference values are similar in majority of standards (ISO 389 1991).

The International Standard (ISO 7029 1984) specifies, for the range of audiometric frequencies from 0.125 to 8 kHz for groups of otologically normal males and females of a given age within the age limits of 18 to 70 years: a. the expected value of the median hearing threshold shift relative to a group of persons 18 years of age; b. the expected statistical distribution above and below the median value. The hearing levels of populations of various ages (males and females) are available in the International Standard, which is based on values which refer to screened populations of otologically normal persons. The data is included in the ISO 1999 1990 standard as “Data Base A”.

The expected noise-induced permanent hearing threshold levels of adult populations due to various levels and durations of noise exposure are available in the International Standard (ISO 1999 1990), which specifies a method for calculating the levels. The data includes “Database B”, which includes the age-related threshold levels for an unscreened population (males and females) of a typical industrialised society.
2.3.2 Noise exposure and its measurement

Exposure level. Equivalent continuous sound pressure level (\(L_{Aeq,T}\)) has gained widespread application as a tool for describing the quantity of long-term noise exposure, both community noise exposure and hearing damage risk (ISO 1999, Directive 2003/10/EC 2003).

The equal energy principle states that the risk of hearing loss is related to the total energy of noise entering the ear independent of the time characteristics of the exposure. According to the principle, doubling the duration of exposure corresponds to a 3 dB increase in the A-weighted sound level. Also, a 5 dB value is used in some countries. The prediction method usually used to predict NIHL is based primarily on data collected with essentially broad-band steady non-tonal noise. The validity of the equal energy principle, however, is not clear. Concerning impulse noise and the equal energy hypothesis, however, the hypothesis may be applicable only over a narrow intensity range (Hamernik et al. 1987); above a “critical intensity” the amount of cochlea damage increases significantly (Roberto et al. 1985).

A sound-level meter device consists of a microphone, an amplifier-attenuator circuit and an indicator meter. Sound-level meters have fast and slow meter response characteristics for different types of noises. They are also equipped with three frequency weighting networks, A, B, and C. Most sound measuring instruments cover a dynamic range of at least 40 to 140 dB SPL re 20 \(\mu\)Pa and may even contain frequency response characteristics and permit measurements in frequency bands from about 0 dB to above 160 dB SPL. When measuring impulse or impact noise, a peak time analysing detector is most common.

A noise dosimeter, which is typically used to evaluate noise risks in occupational health care, is a noise meter that integrates noise samples over time, taking several samples per second. Tape recording is helpful in noise recording, like when measuring aviation noise levels and frequencies in real conditions.

Frequency analysis. Frequency is associated with the perception of pitch. The frequency of a sound is inversely related to the wavelength of the sound, such that low-frequency sounds have a long wavelength and high-frequency sounds have a very short wavelength. Wavelength has a great deal to do with sound penetration. Low-frequency sounds travel easily over long distances. Low-frequency sounds (long wavelengths) are extremely difficult to attenuate or absorb, and therefore the attenuating ability of hearing protectors is less effective at low frequencies. Noise of low frequencies under 500 Hz, produced by large calibre weapons, aircraft rotor blades and engines, etc., are typical in military aircraft (Gasaway 1969, Starck & Kuronen 1990, Wägstaff et al. 1996). Fortunately, low frequency noise exposures have been claimed to be less damaging to hearing than higher frequencies. Indeed, according to some laboratory studies it seems (Hellsström & Dengerink 2001) that low-frequency exposure in combination with high-frequency exposure results in less NIHL than high-frequency exposure alone. If true, the explanation might be that the protective effect of the sound transfer function is dependent on the physical properties of the outer ear canal, the pinna, the head and the torso. On average, a resonance peak is located at 2.5 kHz in the 1/3 octave band and results in 15 dB amplification (Hellsström & Dengerink 2001).
A complete description of the various frequencies present in sound requires the use of a frequency analyser. The most common ones are the FFT (fast Fourier transform) real-time analyser and the 1/3 octave band real-time analyser. The 1/3 octave band analysis is considered to give the best approximation of the critical bands which are used in human auditory processing (Michael & Michael 1993b).

### 2.3.3 Noise-induced hearing damage at high frequencies

Noise is said to begin to damage, earlier than others, the hair cells at the basal end of the Corti organ, where high frequencies are detected (Fausti et al. 1979, Laukli & Mair 1985). Therefore, EHF audiometry might reveal the start of hearing deterioration in military pilots.

Hearing loss in the 3–6 kHz range might be associated with high-frequency impairment (Sataloff et al. 1967). It has been noticed that 0.25 kHz pure-tone exposure caused a TTS also in the high-frequency (HF) range, in addition to the expected TTS at a half to one octave higher than the exposure frequency (Fritze & Köhler 1985). Many theories attempt to explain why the basal area of the cochlea is more vulnerable to noise. Several hydrodynamic effects have been proposed as possible contributors to basal noise-induced damage. These factors include: (1) greater travelling wave amplitudes at the base; (2) greater acoustic load at the base; and (3) a possible basal locus for shock from impulse energy abnormally conducted to the cochlea (Fausti et al. 1981). In animal studies, a decrease of threshold shift or “toughening” was noticed to be more rapid with high-frequency exposure than with similar low-frequency exposure. The underlying mechanisms are not clear, but the persistance of “toughening” at low frequencies might be indicative of the acoustic reflex being the moderator of “toughening” at low frequencies (Subramaniam et al. 1991).

### 2.3.4 Impulse noise

Noise has been classified according to the time variation of the sound pressure level into continuous, intermittent noise, and repetitive discrete, or separated single impulses. Impulses with repetition rates of more than 10 impulses per second have been considered as a semicontinuous impulse noise. Several parameters can be measured in the time domain from impulses: peak level, rise time, decay time, repetition rate, and frequency content (IEC651 1979). In a typical working environment, impulses are seldom identical, but commonly consists of impulses spaced randomly in time and mixed with background noise. In the literature, sometimes the term impact noise has been used only for the collision of rigid bodies in contrast to impulse noise, which often refers to explosion phenomena. Often, however, both terms refer to the same issue. Impulse durations may vary from tens of microseconds for small-arms fire to several hundreds of milliseconds for a sonic boom or a reverberating industrial impact. The intensities of these impulses may vary from less than 100 dB to in excess of 185 dB peak SPL. The measurement and analysis methods of impulse noise is only partly standardised IEC651 1979, ISO 10843 1995,
CENT/TC 159 Technical Committee 2001, Nato 2003). The centre frequency of notches due to impulse noise from gunfire is said to be 5.9 kHz (Gravendeel & Plomp 1958) whereas notches due to long-term noise exposure might have a lower centre frequency, around 4 kHz. (Ward et al. 1961).

2.4 Hearing

The weakest sound pressure that an intact young human ear can detect in a very quiet environment is said to be about 20 µPa at 1 kHz, which was decided to be used as a base reference. The base value is dependent on the exposure frequency (ISO 389 1985). The usual noise levels in industrial workplaces varies from 70 to 120 dB, and for firearms the peak noises are 140–200 dB. Higher pressures can cause discomfort, pain and even destroy the inner ear. Because of such a great range of sound pressure levels, it is usual to express the value on a logarithmic scale in decibels (dB).

Sound evokes physiological responses, e.g., in the ear and auditory pathways. However, not all sounds evoke auditory responses. Ultrasound has too high a frequency and infra-sounds are too low to evoke auditory responses.

The sensitivity of an ear and the effects of noise depend strongly on the frequency of sound-pressure oscillation. The human ear is more sensitive in the frequency range of 1–3 kHz than it is in the range below 0.5 kHz or above 4 kHz (Davis 1998). The sensitivity of human hearing to pure tones deteriorates progressively with age, and the impairment of hearing is more rapid for high-frequency tones. The magnitude of this effect varies considerably between individuals and populations (Rosen et al. 1964).

2.4.1 General aspects of occupational noise-induced hearing losses in Finland

Occupational noise induced cochlea damage is usually caused by long-term work-related exposure to noise. An explosion-type noise may also cause mechanical damage to the ear drum or the ossicles, which is considered an occupational accident. On the other hand, such a single exposure may cause inner ear-related hearing loss.

Most hearing losses, however, result from exposure to continuous, steady-state noise. Sources of noise include machines, air conditioning, transport vehicles and traffic, construction work, maintenance procedures, home appliances and leisure-time activities. In addition, military work exposes persons to the noise of firing, explosions and loud machines. In Finland, cases of occupational diseases or suspected occupational diseases reported by physicians are monitored by means of a register of occupation-related illnesses (Finnish Institute of Occupational Health 2003). The number of reported NIHLs in Finland has decreased since the mid-1980s and were reported in 2001 totally 744 and in 2002 totally 821 persons. In nearly 70% of the cases the hearing impairment was minor and did not reach the level required for compensation at the time it was diagnosed.
More than 90% of persons with a NIHL are males, and impairments were most common among 50–54-year-olds. By occupation and in proportion to the labour force, NIHLs were reported most frequently in mineral mining, vehicle manufacturing and production of pulp, paper and paper products (Finnish Institute of Occupational Health 2003).

Fifty-nine cases of NIHL were reported in military personnel in 2000 (Finnish Institute of Occupational Health 2002). Of these, however, occupational disease reports of hearing loss among air force pilots are nowadays quite infrequent, and even then the link between hearing loss and flight noise has not been assessed in detail. Since the early 1980s, monitoring and prevention of noise-induced hearing effects have become more effective. The hearing of the FiAF flight personnel has been monitored since the 1970s by means of regular annual examinations using audiometric threshold measurements.

The development of NIHL is affected by many factors, such as individual sensitivity, noise level, duration of exposure, noise characteristics, the proportion of impulse noise and the effectiveness of noise protection (Henderson et al. 1993). Persons with NIHL sometimes report intermittent or continuous tinnitus in their ears. According to Mrena et al. (2002), 29% of conscripts who had AAT during their service and were treated, still reported tinnitus after 10 to 15 years from the AAT (Mrena et al. 2002). The NIHL may cause social interaction difficulties due to discriminated perception of speech, fluctuation in loudness and problems with temporal integration of sound signals. Incipient damage of the inner ear is often first detected in hearing measurements as an impaired hearing threshold at 3–6 kHz (ISO 1999 1990).

There are major individual differences in the inner ear’s sensitivity to noise-induced hearing loss, although the reasons are not clear. The NIHL is bilateral and substantially symmetrical. However, these main characteristics may vary. TTS was shown to be greater at 4 kHz in the left ear with test persons who had not exposed to shooting, even though the level of significance was only indicative (Pirilä et al. 1991). One possible explanation for ear asymmetry, especially in the male population, might be that a right handed person is usually shooting the rifle on the right shoulder, and that this position exposes the left ear more than the right ear to impulse noise (Anttonen et al. 1980, Cox & Ford 1995). However, the hearing thresholds of populations exposed to occupational noise indicate that the left ear might be more susceptible to noise damage than the right ear (Kannan & Lipscomb 1974). The aetiology of the possible left-right asymmetry in susceptibility to noise damage is not clear.

For the same noise exposure conditions, the magnitude of a PTS at 4 kHz varies greatly. It has a significant tendency to increase with age and working life duration (Sallustio et al. 1998). As the PTS in the 3–6 kHz range increases, the adjacent frequencies are usually involved (Quaranta et al. 1998). Speech perception in quiet surrounding is related to the hearing level at 2 and 4 kHz (Humes et al. 1979). Particularly significant for the speech discrimination is the involvement of frequencies below 3 kHz, where speech components are present. Studies indicate that in subjects affected with NIHL, several psychoacoustical performances are altered in conditions of functional stress of the hearing system, for example, difficulty in the perception of speech in background noise (Humes et al. 1979, Humes 1983, Quaranta et al. 1998).

When examining work-related hearing loss it is necessary to also evaluate non-work-related exposure. Military work exposes persons to the noise of explosives and firearms.
Exposure to noise when pursuing leisure-time hobbies makes assessment of the long-term effects of flight noise and the risk of hearing loss difficult. The use of medication, health risks and various illnesses that affect the inner ear may also make a person susceptible to hearing loss (Ylikoski 1994, Toppila et al. 2000).

Information about exposure to noise, both occupational and non-occupational, the characteristics and the use/non-use of hearing protectors is necessary when assessing a person’s noise-induced hearing impairment. Besides, sufficient audiometric information (at least pure tone audiometry, including bone conduction measurements and speech differentiation) is also required for evaluation of work-related NIHL.

### 2.5 Harmful effects of noise and noise in military aviation

#### 2.5.1 Origins of noise

In military aviation noise is caused mainly by different types of engines and mechanical transmission systems. Subjectively, launches of aircraft missiles, gun firing or aerodynamic noise do not usually cause harmful noise, but noise measurements during firing are not carried out in the FiAF.

The noise exposure of pilots depends not only on the design of each aircraft type, the noise level in the cockpit, and noise caused by radio communications, but also on the power settings required in different flight conditions, as well as on aerodynamic noise (Bray 1976). When starting the engines on platforms, the auxiliary power starters cause significant noise during the operational use of jet fighters.

#### 2.5.2 Noise levels and frequencies

Usually, noise exposure in military aircraft is emphasised at lower frequencies. At low frequencies (less than 0.1 kHz) the noise level is higher inside the helmet due to the occlusion effect of the ear, which means that noise can be amplified in the closed ear canal because of resonance (Berger & Kerivan 1983). At higher frequencies (0.2–10 kHz) the noise attenuation of helmets has been shown to be 5–25 dB, depending on the type of jet fighter and helmet and the amount of communication during the flight sortie (Starck & Kuronen 1990).

Propeller aircraft cause low-frequency noise. The blade frequencies indicate that this noise has the most significant energy in the frequency range of less than 0.5 kHz. Although low-frequency noise is an important source of noise exposure in these planes, this frequency area has been studied very little in aviation. Some authors point out the nonauditory effects, like fatigue, of low-frequency noise (Brown et al. 1975, Broner 1978, Landström 1983, Landström & Löfstedt 1987)
2.5.3 Exposure levels of the personnel

In a large compendium of noise measurements in numerous aircraft, mean cockpit noise levels ranged from 95 to 105 dB(A) and all mean A levels exceeded the damage risk criterion for 8 h/day exposures. Hence, hearing impairment has been considered possible, especially during prolonged exposure (Gasaway 1986).

Radio communication noise causes different levels of noise exposure, depending on missions, protection, and communication equipment, and also very much on the volume of the transmission (Wagstaff & Woxen 2001). Radio communication noise, which is partly impulse-type noise, has been found to cause an exposure rise of up to 11 dB from the level of background noise (Starck & Kuronen 1990). Impulse-type exposure may also increase the risk of noise-induced damage in animals (Hamernik et al. 1993) and increases the risk of noise-induced inner ear damage more than pure continuous noise as estimated on the basis of the steady-noise equivalent principle (Mäntysalo & Vuori 1984, Henderson & Hamernik 1986).

Aircraft carriers present probably the noisiest military aviation environment. During take-offs landing signal officers can be exposed to an average SPL of 131 dB, which means an average noise level of 121 dB(A) (Robertson et al. 1982).

The noise inside a jet fighter cockpit and on platforms is high. Therefore, noise surveys and audiometric testing of pilots have been done (Stone 1969, Robertson & Williams 1975, Starck & Kuronen 1990). However, the real noise exposure of pilots outside and inside the helmet during flight missions have been less studied. In practice, protectors have frequently been found to have leaks and other defects, which reduce their sound reduction properties (Berger 1986, Pääkkönen 1992, Wagstaff et al. 1996).

In helicopters, depending on the type, noise levels of 97 dB(A) to 100 dB(A) were measured before attenuation at the ear level (Gasaway 1969). According to research on US Army helicopter pilot research, there seemed to be a risk for hearing loss due to excessive noise exposure (Fitzpatrick 1988).

2.5.4 Flight safety issues

Speech intelligibility. Speech intelligibility is adversely affected in a noisy environment. A primary effect of noise is masking of voice communication signals at both the talker and listener locations. The frequency bandwidth of U.S. Air Force standard voice communication systems and equipment is approximately 0.3–3.5 kHz. Noise spectra with substantial energy in this speech frequency region, and slightly below, are most effective in masking speech signals (Nixon et al. 1998b). The speech spectra were found to be similar for average male and female speech, however, the acoustic components of the average female voice differed in frequency from those of the male. The average speech power for males was about 34 µW and for females about 18 µW, which was estimated to correspond to a difference of about 3 dB at a conversational speech level. The female speech level was found to become less intelligible at higher noise levels, such as the cockpit noise level of 115 dB (Nixon et al. 1998a). Most of the acoustical energy of speech is in the frequency range of 0.1–6 kHz, depending partly on the language. The
The most important cue-bearing energy is between 0.5–4 kHz (Jauhiainen 1995). Environmental noise may also mask other acoustical signals, like warning signals in aviation (Berglund et al. 2002).

The reduction in speech intelligibility is partly related to a masking effect. Increased masking of low frequencies is caused by high-frequency noise (Quaranta et al. 1998). On the other hand, extra low-frequency noise can be increased in the inner ear by noise leakages that vary depending on the position and movement of the head and how the headset and glasses are fitted (Wagstaff et al. 1996). Background noise in the cockpit combined with noise from radio communications may reduce the intelligibility of transmission (Stone 1969, Tobias 1969). Headsets were shown to improve the intelligibility compared to cabin loudspeakers because of better signal-to-noise ratio in general aviation (Townsend 1978). On the other hand, double hearing protection is often used by pilots under headsets and flight helmets. In the FiAF, fibre plugs or foam plugs are usually used as extra attenuation inside the helmet. Sometimes pilots using double protection complain about having to maximise the of radio transmission for speech intelligibility, causing a situation with no reserve volume and poor sound quality. In helicopter noise, wearing foam ear plugs under the headset decreased speech intelligibility dramatically, which may be because earplugs attenuate better the higher frequencies which are important for speech intelligibility (Wagstaff & Woxen 2001).

**Vigilance.** Noise and vibration, which are usual physiological exposures in military aviation, are thought to increase fatigue and thereby jeopardise flight safety. Even though these factors might be involved in wakefulness, the relationships between the many other physiological and psychological factors present during military missions is a very demanding area of research, and the conclusions are not clear (Landström & Löfstedt 1987). Noise can also act as a distracting stimulus, and impulsive noise events may produce disruptive effects as a result of startled responses (Berglund et al. 2002).

**Other issues in military aviation.** Military aviation presents a complex and demanding working environment. Exceptionally demanding exposures include low ambient partial oxygen pressure, dry breathing air (Vieillefond et al. 1977), vibration induced by aircraft engines and turbulence (Landström & Löfstedt 1987). With fighter pilots, the breathing gas supplied by the life support system produces a high partial oxygen pressure as a function of altitude. Again, with fighter pilots, acceleration forces produced by maneuvering an aircraft impose loads on the circulatory system and reduce blood circulation at the central nervous system level (Siitonen 2000). Data on the effects of acceleration on blood circulation or fluid kinetics in the inner ear are not known. Information flow can easily overshoot the information processing abilities of a pilot. Thermal load, low ambient pressure and a dry respiratory gas mixture can stress a pilot. Vision is the most important sense in aviation.

Concerning flight safety, the processing information flow from many senses can easily distract the attention of a pilot (Bagian & Rosekind 2002). Due to the great number of variables, it is difficult to assess the significance of aviation noise and health risks to pilots’ hearing at an individual level (Thomas et al. 1981).

Some other health risks may be associated with aviation noise. Increased periodontal disease in aircrew members was shown be associated with exposure to propeller aircraft noise and vibration (Haskell 1975). It has been claimed that aviation noise might increase cardiovascular risks of aviators, but no associations were found in the aircrew population.
(Brown et al. 1975, Kent et al. 1986). In the group of aviators with no hearing threshold abnormalities compared to the group with impaired hearing, the comparison of 33 biomechanical, psychological and behavioral variables indicated that persons who smoked and who had blue eyes might have increased risk for hearing impairment (Thomas et al. 1981).

### 2.5.5 Effects of military noise

An AAT is caused by a sudden high level of noise pressure, typically an explosive type. It can cause mechanical injuries in the middle ear and inner ear. Most seriously, as a consequence of ruptures of membranes of the inner ear, the endolymph and perilymph can be mixed, causing a full loss of hearing. In these cases the damage depends on single noise impulses, not on the total energy level (Sataloff & Sataloff 1993).

Possible sources of AAT can be weapons and explosions or noisy leisure time hobbies, like music (Pekkarinen 1995). However, reports concerning aviation noise and AAT were not available. The factors influencing the severity of hearing damage are the peak level, spectrum and duration of the sound burst, and individual sensitivity. Subjective symptoms are fullness of the ear, tinnitus and elevation of the threshold (Ylikoski & Ylikoski 1994). The hearing loss can change during the following days or months; in mild conditions the damage recovers spontaneously and in severe cases the degree of damage can partly recover or remain permanent.

A TTS recovers usually completely within 24 hours after exposure to loud noise for seconds-to-hours (Kyong-Myong et al. 1996). A TTS induced by impulse noises (rifle calibre weapons) without hearing protection was found to be recovered in most cases 24 hours after the exposure and in all cases 3 days after the exposure. Tinnitus arose almost always just after the exposures (Dancer et al. 1991).

Salmivalli (1967) reported that age-corrected hearing loss was found in 33% of army staff personnel in the Finnish Defence Forces after five years of service, and in 69% after 20 years of service. Moreover, because of continuing exposure, even those individuals who were resistant to acquiting NIHL suffered hearing damage, which continued in severity during the time period they were studied (Salmivalli 1967). The rules, habits and protection equipment, which have been aimed to improve hearing protection, have changed very much from 1970s. In a later study among professional soldiers, age-correlated NIHL was found in 50.4% of the subjects (Ylikoski & Ylikoski 1994). The pressure level during shooting depends on, besides protection, the type of gunfire, distance and shelter (Pääkkönen et al. 2000c). NIHL was unilateral in Finnish conscripts (81.3%) at higher frequencies (4.0–6.0 kHz) (Savolainen & Lehtomäki 1997).

### 2.5.6 Temporary threshold shift caused by military aviation noise

The relationship between a TTS and a PTS is questionable (Henderson et al. 1993). However, it has been suggested that a TTS could predict a PTS, or a TTS in any cause may serve as an indicator of harmful noise levels. On the other hand, fairly recent find-
ings from animal studies seem to indicate that the development mechanisms of a TTS and a PTS are not identical and a TTS may not necessarily predict a PTS (Nordmann et al. 2000).

Persons who are exposed to noise at work may be exposed to other factors that increase the risk of a PTS or give rise to a TTS. The noise of firearms, loud music, and other exposure related to leisure activities often results in significant noise exposure, causing a TTS (Pekkarinen 1995). Animal studies have yielded extensive information on the TTS (Clark 1991), but the results should be applied with care when examining the pathophysiology of hearing loss in humans. Individual factors are also widely associated with hearing deterioration and a TTS (Henderson et al. 1993, Quaranta et al. 1998).

Many factors may render individual humans sensitive to a TTS. The frequencies affected by a TTS are related to the noise spectrum, typically the wide band type in common occupational conditions. In these cases, the TTS is more pronounced in the frequency range from 3 to 5 kHz, probably due to ear resonance and the effect of the stapedius reflex (Gerhardt et al. 1987, Quaranta et al. 1998). Smoking (Dengerink et al. 1992) and a high blood cholesterol content (Axelsson & Lindgren 1985) may increase susceptibility to a TTS. A high oxygen content (90–100%) in breathing gas has been claimed to reduce the rate of TTS development (Patchett 1980). Good aerobic performance may prevent the development of a TTS (Kolkhorst et al. 1998). It has also been proposed, among other things, that blond persons who have little melanin in their stria vascularis, are more susceptible to a TTS (Barrenäs & Lindgren 1990).

In military aviation, depending on the aircraft type and mission, pilots are subjected to different forms of exposure, which may predispose them to a TTS in a noisy environment. Low ambient partial oxygen pressure may expose them to a TTS (Pierson 1973). Vibration is also shown to increase susceptibility to a TTS (Yonekawa et al. 1998).

Only a few reports concerning TTS caused by aviation noise are available. After 5 minutes of exposure to 117–128 dB(A) of a military jet’s ground running-up noise without ear protection, a TTS was noticed in ground personnel. The TTS was more than 13 dB and at a maximum at 4 kHz. The TTS recovered in 30 minutes at low and speech frequencies, whereas the TTS at high frequencies recovered more slowly and returned to normal only 24 hours later (Wu et al. 1989).

### 2.5.7 Permanent noise-induced hearing loss from military aviation noise

Surveys of military pilots in the United States showed that hearing acuity decreased with age. Pilots also had better hearing than the general population, but tended to lose their hearing more rapidly at 6 kHz. No specific efforts were made in the survey to identify the effects of noise exposure associated with flying on hearing (Sutherland et al. 1967). A statistical evaluation of hearing losses in Swiss military pilots revealed that ageing was the most significant factor influencing the threshold shift of the test group of 673 pilots and their 5786 audiograms (Schulthess & Huelsen 1968). It has been considered that the threshold shifts discovered among pilots have largely resulted from ageing, and no defini-
tive correlation has been found between aircraft types, exposure, and the threshold shift (Ribak et al. 1985).

The results of the study conducted on US Army helicopter pilots indicated that the total number of flight hours was the major risk factor, while ageing and aircraft type constituted minor risks (Fitzpatrick 1988). The risk of hearing impairment among helicopter pilots of the United States Army was related more to the length of their flying career measured in years and the person’s age than to the number of flight hours (Owen 1996).

The results of the studies are, therefore, contradictory, but ageing has proved to be the most clearly established risk factor. No recent literature has been available on the risks of hearing impairment in civil aviation, but earlier literature suggests that the risk of hearing impairment among airline pilots is low (Kronoveter & Somerville 1970).

Periodic medical examinations of pilots have revealed threshold shifts, also, pilots are concerned with the effects of aviation noise. Finnish military pilots participate in annual service firings using small-caliber arms; during these firings, an estimated 100 rounds are fired, which also contributes to the risk of occupational NIHL (Ylikoski 1994).

### 2.5.8 Assessment of the risk of noise-induced hearing loss

The ISO standard 1999 (1990) gives a method for estimating noise-induced hearing impairment that includes age in populations exposed to all types of noise (continuous, intermittent, impulse) during working hours. The standard should also be used to calculate hearing impairment due to noise exposure from environmental and leisure time activities. The ISO standard 1999 (1990) implies that long-term exposure to $L_{\text{eq,24H}}$ noise levels up to 70 dB(A) will not result in hearing impairment. To avoid hearing loss from impulse noise exposure, peak sound pressures should never exceed 140 dB for adults, and 120 dB for children.

Sound-level meters are normally equipped with three weighting networks, A, B, and C, that can be used to approximate the frequency distribution of noise over the audible spectrum. A, B, and C filters were intended to match the auditory system’s response curves at low, moderate, and high loudness levels, respectively. The A-weighting curve approximates the ear’s response characteristics for a low level sound, below 55 dB re 20 $\mu$Pa. It is used to weight sound pressure levels as a function of frequency, approximately in accordance with the frequency response characteristics of the human auditory system for pure tones. Energy at low and high frequencies is de-emphasised in relation to energy in the mid-frequency range. The B frequency weighting is intended to approximate the ear’s response at levels between 55 and 85 dB, and the C-weighting corresponds to the ear’s response at levels above 85 dB (Michael & Michael 1993b). A D filter is fairly seldom used nowadays, even though it was originally developed to approximate air traffic noise.

The A-weighting is widely used for sound level measurements in a variety of situations and especially to approximate the risk of hearing damage. The measure of exposure to noise for a population at risk is averaged A-weighted sound exposure (time-integrated squared sound pressure), $E_{A,T}$, and the related equivalent continuous A-weighted sound pressure level, $L_{\text{eq,T}}$, over an average working day, for a given number of years of expo-
sure (ISO 1999 1990). For sounds in a narrow frequency range, considerable care must be exercised in the interpretation of A-weighted sound pressure level readings, since they may not accurately reflect the loudness of the sound. Indeed, the dB(A) value may overestimate NIHL, especially at frequencies lower than 2 kHz (Hellström & Dengerink 2001). Also, A-weighting predicts loudness and annoyance of the community rather poorly (Berglund & Lindvall 1995b).

The effects of a combination of noise events is related to the combined sound energy of those events (the total energy principle). Currently, the recommended practice is to assume that the equal energy principle is approximately valid for most types of noise and that a simple $L_{Aeq,T}$ measure will indicate the expected effects of the noise reasonably well. When the noise consists of a small number of discrete events, an A-weighted maximum level ($L_{Amax}$) can be used as an indicator. In most cases, however, the A-weighted sound exposure level provides a more consistent measure of single-noise events because it is based on integration over the complete noise event.

A new personal risk evaluation database for NIHL, called the NoiseScan model, has been developed in Finland. Individual risk factors are taken into account in the NoiseScan model (Pyykkö et al. 2000). The NoiseScan model predicts that a person with a small number of risk factors is less vulnerable to noise than a person with a large number of risk factors (Toppila et al. 2001). If the new risk models (Starck et al. 1999a, Pyykkö et al. 2000, Toppila et al. 2001) could be used for the consideration of all contributing factors in assessing the risk of an individual’s susceptibility, the prediction, prevention, and treatment of NIHL could be improved.

### 2.5.9 Hearing surveillance

According to the rules of the FiAF, the pilots have to have annual audiometry examination for a frequency range of 0.25–8 kHz conducted in a sound-proof test booth which meets standard specifications. The check-ups also provide information about hearing protection. Very seldom are restrictions for flight duties needed. Extended high-frequency audiometer measurements have been used only for research programme purposes.

Depending of their duties and noise exposure, audiometry is provided for technicians and maintenance personnel every 1–3 years in Finland.

### 2.6 Noise control in military aviation

#### 2.6.1 Reduction of radiated noise

Radiating noise can be controlled by enclosures, barriers, isolation procedures, or by the use of noise control procedures in order to obtain an acceptable noise level. All these methods are used, when possible, in noise prevention in military aviation. The choice depends on several factors including: 1. position of the noise source with respect to the
exposure area, 2. acoustical characteristics of the surrounding area, 3. frequency spectrum of the noise, 4. amount of noise reduction required.

General issues concerning military aviation operations. Environmental aviation noise protection can be difficult in real operational conditions because there are many noisy aircraft on the same platform at the same time. Sometimes separate shelters can reduce environmental noise, but then noise exposure for technicians can be even more harmful than on the open platform. Auxiliary engines in jets often cause fairly high noise when they are started. Hearing protection is mostly dependent on personal protection. Test running of engines is usually done in special “sound proofed” building where the engine is in a separate room and noise is conducted outside by a separate pipe. Measurements are carried out by instrumentation in a separate well-isolated room. Such noise protection is very effective both for the environment and personnel.

Vibration damping and isolation. Vibration amplitudes are directly related to the noise level produced; thus, a reduction of mechanical vibration amplitudes may also be a very effective noise control measure. The thickness (or weight per unit area) of the vibration damping material is related to its effectiveness.

Damping can be used in certain places like in the buildings where test running of the engines is carried out. Vibration isolation can be used where separate shelters can be used in operations (Michael & Michael 1993a). However, in military operations, the most important requirements of the shelters’ structures are concerned with protection from wartime hostile effects.

2.6.2 Personal protection

In military aviation, structural or other protection procedures are not effective enough or able to prevent harmful noise exposure of workers. Therefore, personal noise protection is needed. Sound energy may reach the inner ears of persons wearing protectors by four different pathways: 1. by passing through bone and tissue around the protector; 2. by causing vibration of the protector, which generates sound in the external ear canal; 3. by passing through leaks in the protector; and 4. by passing through leaks around the protector (Sataloff et al. 1993).

It is obvious that in real working conditions, the noise attenuation results of protection devices are below the levels achieved in laboratories or given by manufacturers. The fitting procedure is particularly important for insertion-type devices (Pääkkönen et al. 2000b). On the other hand, the attenuation of protectors depends significantly on the users’ behaviour and the working situation, like perspiration, head movements, speaking and swallowing. In addition, depending on the noise frequency range, the attenuation abilities of different protectors or their use in combination differ from each other (Park & Casali 1991).

There have been major developments in passive hearing protection during the past few years. In the United States a new method for determining real-ear attenuation at the threshold has been adopted. This method seeks to obtain laboratory data that are predictive of real-world, work-site outcomes for workers using hearing protection. Repeated work-site
and real-world studies have provided evidence that showed that protection seldom, if ever, reaches or exceeds the attenuation rates achieved in laboratories (Franks 2001).

In military aviation, noise attenuation abilities are only one specification of helmets and headsets. They must also give space for communication solutions and besides, the structure must be effective for survival ejections up to speeds of 450–600 knots (830–1100 km/h). In practice, all the protectors, including helmets, have been found to have leaks and other defects which deteriorate their sound reduction properties (Berger 1986, Pääkkönen 1992).

**Inserted or plug protectors.** The material of insertion-type protectors can be rubber, silicone, plastic, wax-impregnated cotton, expandable foam, or other materials. The best attenuation can be achieved by sized plugs which are even personally fitted to the individual.

Dry cotton gives very little protection. Fibre plugs provide attenuation of 12.6–18.8 dB in the range of 0.125–1 kHz, respectively (Berger 1983). Malleable plugs made of nonporous and easily formed materials are capable of providing attenuation values equivalent to those provided by the best sized-type molded earplugs and many earmuffs. Plugs must be carefully formed and inserted to obtain good performance. In military aviation, however, trapped air volume changes in the ear canal must be taken into account during great atmosphere pressure changes (Bragg & Danford 1972). When different ear plugs were tested against heavy weapon noise on Finnish army conscripts, the fitting procedure was found to be crucial and the attenuation varied from 16 to 23 dB(A) (Pääkkönen et al. 2000c).

**Earmuffs.** Most muff-type protectors have similar designs. The seal materials placed against the skin are nontoxic, and the fit, comfort factors, and general performance of comparable models do not vary much. A larger-volume muff provides increased attenuation relative to a small-volume muff from 0.125–1 kHz, since in this region the increased volume and mass of the cup are the controlling physical parameters. Also, heavier material attenuates better against low frequencies (Berger 1983). When different earmuffs were tested against heavy weapon noise with Finnish army conscripts, the attenuation was from 10 to 20 dB(A) and earmuffs with large-volume cups worked significantly better against low-frequency weapon noise (Ylikoski et al. 1995, Pääkkönen et al. 2000a).

**Helmets.** Flight helmets are specified primarily for survival protection during ejections and after parachute landings. Because of neck strain during acceleration forces, the weight of helmets is reduced as much as possible by using light materials like Kevlar® and carbon fiber structures (Hämäläinen 1993). Communication and hearing protection are secondary characteristics compared to impact protection. In the latest helmets, the weight has again increased because of the extra load of night vision goggles and helmet-mounted sights.

A special noise helmet could reach an attenuation of roughly 50 dB and thus provides 18–29 dB more attenuation than earmuffs in the frequency range of 0.125–8 kHz (Pääkkönen et al. 1991).

Noise attenuation properties of flight helmets have been studied. The design of the helmets is mainly focused on protection properties in emergency situations, fitting and stability properties during the flight missions (Carter 1992). However, only a few reports concerning helmets have been published (Ivey et al. 1987, Pääkkönen & Kuronen 1987).
Active noise cancellation. The latest innovation in improving hearing protection in a noisy environment is an active noise cancellation (ANC) device, which is usually installed in the earmuffs of a headset or helmet in combination with a communication system or without it. There are nowadays numerous potential applications commercially available for aviation use. An ANC headset or helmet works by continuously sampling the noise inside the earmuff using a miniature microphone. The noise is then inverted 180° by an electronic circuit and reintroduced through an earphone speaker. The destructive interference cancels out the original noise. However, the ANC systems are only effective in the low-frequency range. An international standard specifies procedures for testing personal hearing protection devices in relation to Directive 89/686/EEC – Personal protective Equipment (CENT/TC 159 Technical Committee 2001). The following principles should be taken into account when the use of ANC is considered in aviation: 1) level and frequency content of environmental noise, 2) attenuation properties of the system (both active and passive attenuation), 3) effects on the communication system, 4) individual experiences.

At its best ANC provides extra attenuation of about 15 dB in the low-frequency region of 0.125–1 kHz. The resonance phenomena peak at frequencies around 2–3 kHz may reduce the attenuation ability at that frequency range (Wagstaff et al. 1998).

Combined hearing protection. During flight missions, pilots use different insertion or plug-type protectors under their helmets and headsets for protection in the noisy aviation environment. A literature search failed to reveal data on noise levels at the ear canal during actual flights. Noise levels inside helmets have, however, been measured during flights by means of a microphone installed at the entrance of the ear canal and at the same time another microphone was installed outside the helmet or headset, thereby, recording cockpit noise (Starck & Kuronen 1990).

For a well-fitted, inserted hearing protection device, such as E-A-R® foam plugs, the benefits to be gained by wearing at the same time an earmuff are primarily in the 0.25–1 kHz region providing attenuation about 15 dB. At the remaining frequencies, the increase in performance is only 4–6 dB. At and above 2 kHz, plug-plus-muff combinations were found to provide attenuation that was approximately equal to that of the human skull, i.e., the combined attenuation was limited only by the flanking bone conduction paths to the inner ear.

Extrapolation of the attenuation data to double protection can lead to erroneous conclusions (Berger 1983). Furthermore, according to Wagstaff (2001), the foam plugs reduced speech intelligibility when used inside the headset. The reasons might be that the additional plugs reduced the communication speech level more than the environmental noise because the low frequency noise was transmitted as bone conduction via the skull. On the other hand, the foam plugs reduced high-frequency noise more than low-frequency noise, and this might reduce the signal-to-noise ratio at frequencies important for speech understanding. On the other hand, the custom-molded plugs which were fitted to each subject’s ear canal gave improved speech intelligibility. Custom-made plugs proved to have a similar attenuation of 15 dB at all frequencies, thus avoiding selective degradation of the signal-to-noise ratio at certain frequencies. Thus, a single good protector may be preferable and simpler, especially in military aviation environment, than wearing two protectors, especially when their combined attenuation is unknown (Wagstaff & Woxen 2001).
Helmets can reduce noise better than earmuffs at higher frequencies because they completely encase the head, blocking noise incidence on the skull, and thus reducing bone conduction transmission. With a specially designed noise helmet, with any type of high-quality earmuffs fitted into the helmet, noise attenuation was improved by 8–13 dB in comparison with the level reached with a set of the highest attenuating earmuffs at frequencies of 0.063–0.5 kHz. An improvement of 18–29 dB was possible at frequencies of 1–8 kHz (Pääkkönen et al. 1991). The combined use of earplugs and earmuffs gave less attenuation values against large calibre weapon noise than expected. If the limit for the C-weighted peak level is 140 dB for an unprotected ear, then protection against low-frequency noise is provided for up to 156 dB by earplugs, up to 150 dB by earmuffs, and up to 165 dB by the combined use of plugs and muffs (Pääkkönen et al. 2000a). According to Ylikoski et al. (1995), the combination of earplugs and earmuffs attenuated the noise of weapons being fired by 25 dB.
3 Aims of the study

The purpose of this study has been:

1. To assess the aviation noise exposure of pilots and partly of maintenance technicians working on the platform (Study II),
2. To evaluate their hearing protection (Studies I, II, III),
3. To assess the risk of a TTS (Study V),
4. To test if a modern database model is suitable for and better at predicting the risk of NIHL than the ISO 1999 standard (1990) (Study VI),
5. To evaluate the risk of sudden hearing loss after jet fighter overflights and to assess claims of hearing losses caused by FiAF aircraft overflights (Study IV).
4 Subjects and methods

4.1 Noise exposure and attenuation abilities of helmets and headsets in laboratory conditions (Study I)

Test subjects. Fighter and helicopter pilots from several air bases were studied. They were professional aviators on active duty, with a mean age of 33 years (n = 35, SD 7 years), no beard and short hair. During each test they sat in an anechoic room at exactly the same site and under the same conditions and they were encouraged not to move or swallow.

Helmets and headsets. In order to obtain reliable data about the noise attenuation properties of military aviation helmets and headsets, a test programme was carried out in an anechoic chamber. The test persons used their individually fitted helmets which they used during flight missions. The following four helmets were tested: Alpha (Helmet Integrated Systems, Wetherhamstead, UK), FFV Flyghjälm 113B (FFV, Sweden), ZSH-5A (MG, Russia) and ACS (Gentex, USA). One Alpha helmet was equipped with an active noise reduction system (Alpha ANR, Helmet Integrated Systems, Wetherhamstead, UK). Alpha helmets are used in the FiAF in Hawk MK 51 jet trainers and helicopters, the FFV Flyghjälm was used in Draken fighters, the ZSH-5A was used in Mig 21 Bis fighters. During the tests, the Gentex ACS helmet was evaluated for F-18 Hornet fighters. With the exception of the ACS, the helmets were adjusted beforehand. The combination of an Alpha helmet and sunglasses (Zeiss Clarlet Skylett, Aalen, Germany, and Randolph Grey-3, USA) which are permitted in the FiAF was also tested in order to obtain data on noise leakage effects. Noise attenuation was also measured as a function of the hearing protector cloth effect. The cloth covers the ear cups of the headsets and helmets.

The two tested headsets and hearing protectors were Ampliguard Amp 3320 (Racal Acoustics, Harrow, Middlesex, UK) and Silenta Super earmuffs (Silenta Ltd, Jyväskylä, Finland).

Measurement methods. The noise attenuation properties of the helmets and headsets were determined on test subjects through a miniature microphone (insertion loss (IL) method) in an anechoic room at the Tampere University of Technology, Tampere, Finland. Pink noise from a self-constructed pink noise generator was fed to an amplifier.
(Technics SU-V5, Matsushita factories, Osaka, Japan), and the amplified signal was conducted to four loudspeakers (ART-H150, 150/300 W, Riga, Latvia). The signal level at different frequency bands was adjusted using a 1/3 octave band equaliser (Technics SH-8075, Matsushita factories, Osaka, Japan) in frequency bands from 0.0315 to 10 kHz. The loudspeakers were at a distance of 1.50 m from the subject at about 90° angles around him. The sound level in the chamber was measured at all times using a precision sound level meter (General Radio 1933, Concord, Massachusetts, USA).

The noise inside the helmets and headsets was measured with a miniature microphone (Sennheiser KE4, Sennheiser Electronic KG, Wedemark, Germany) and then amplified by a precision sound level meter (B&K 2209, Naerum, Denmark). The microphone cord (1.5 mm) ran between the cushion and the skin, which caused an error according to earlier experiments, less than 2 dB (Pääkkönen & Tikkanen 1991), in the results. The signal was analyzed in 1/3 octave bands with a real-time analyzer (B&K 2131), the averaging time being more than 30 s. The results were processed and printed by a Hewlett-Packard 310 computer. During the measurements, the pink noise detected by the microphone near the ear canal was first adjusted to be 80 ± 1 dB at 1/3 octave bands of 0.063–8 kHz. Then the protector was fitted on the subject and the 1/3 octave bands inside the protector were recorded. Afterwards, the sound levels in the 1/3 octave bands with and without the protector were subtracted from each other. The averages and standard deviations of the results of the subjects were calculated for each protector combination.
4.2 Noise measurements of exposure and attenuation abilities of helmets, headsets and earmuffs in real working conditions (Studies II–III)

Fig. 1. The arrangement of the research equipment: miniature microphones, one attached outside the helmet, one at the entrance of the ear canal. The two channel digital tape-recorder was connected to microphones and installed into the pocket of the flight suit.
A total of 27 pilots with helmets and 10 pilots with headsets were included in these tests. Noise measurements were made in Finnish F-18 Hornet, Saab 35 Draken and Mig 21 Bis jet fighters, Hawk BAe MK 51 jet trainers and Finnish Valmet-made Vinka basic trainer and Redigo liaison aircraft, as well as Piper Cherokee and Piper Chieftain liaison aircraft and Fokker Friendship transport aircraft. The measurements were carried out during pilots’ routine flight rounds at their own air bases. The pilots used a Gentex helmet in the F-18 Hornet, a FFV Flyghjälm helmet in the Draken, a ZSH-5A helmet in the Mig and an Alpha helmet in the Hawk, Vinka and Redigo. All the helmets were personally adjusted beforehand for the pilots. The volume of the radio communication was set freely by the pilots. In other aircraft the communication headsets were used.

The noise exposure was evaluated by noise dose meters (MIP 6074, MIP Oy, Finland) outside and inside the flight helmet. The outside noise dose was measured above the seat belt on the shoulder and the inside noise dose was measured near the ear canal in the right ear of the pilot by a miniature microphone (Knowles BL 1785, Knowles Inc, Illinois, USA). The microphone cord (diameter less than 1.5 mm) ran between the skin and the cushion of the helmet, causing some error in the measurement results, but according to an earlier study the error is small (less than 2 dB), and it was the same for all measurements (Pääkkönen & Tikkanen 1991). The noise dose meter was started after the pilot had received his flight task in the flight squadron, and the meter was read after the pilot was back at base. Therefore, the noise doses contain exposure before and after the jet engine was started or stopped. The noise results of similar plane types were indicated as mean values and their standard deviations (SD).

For continuous time and frequency analyses, a two-channel tape-recording system was constructed where two miniature microphones (Sennheiser KE4, Sennheiser Electronic KG, Germany) were connected through a self-constructed amplifier to a digital tape recorder (Sony TCD-D7-8, Sony, Tokyo, Japan). These two microphones were set similarly as in the noise dose measurements, but on the left ear and left shoulder of the pilot. The microphone cords were routed inside the flight suit into an angle pocket of the suit for safety reasons (Fig. 1). The tape-recorded samples were analysed and averaged over the flight (from the time the engine was started to when it was stopped) in the frequency domain by a real-time analyser B&K 2131 and instantaneously in the time domain as an A-weighted noise level (F time constant) by an amplifier, an A-weighting filter and a B&K 2307 recorder. The background noise levels (cockpit noise into the flight helmet) and noise levels caused by the radio were evaluated from the time analyses. The results were again expressed as the means and SDs for similar plane types.

From the measured values it was also possible to calculate the exposing noise in the ear canal from the cockpit noise (by using the attenuation values of the helmets and earmuffs) and the significance of the radio noise.
4.2.2 Earmuffs

A total of 33 maintenance technicians were included in these tests. They used Silenta Super earmuffs and a noise dose meter (MIP 6074, MIP Oy, Finland) during one day, and the noise doses mainly represent the noise dose of the technicians working on the platform sending and receiving planes.

4.2.3 Measurements of active noise cancellation devices

Active noise cancellation devices were not used operatively in the FiAF at the time of the tests. Noise was measured in the following types of Finnish military propeller aircraft: Piper Cherokee, Piper Chieftain, Redigo and Fokker Friendship. The measurements were carried out during normal flights at the pilots’ own air bases. The pilots or passengers used a Gentex helmet (PRU-57/P in HGU-55/P)/with Bose (Bose Corp, Framingham, USA) ANC device, an Alpha 200 series ANC helmet (Helmet Integrated Systems, Wheathampstead, UK), a Sennheiser HMDC 222 Noise Guard headset (Sennheiser electronic KG, Wedemark Germany) and an RA 155 Atlantic headset (Racal Acoustics, Harrow, Middlesex, UK). The helmets were not adjusted to fit the users before the flight. There was no radio communication inside the headsets or helmets, and therefore actual communication was not measured or analysed.

The measurements for the continuous time and frequency analyses were carried out according to the method described in chapter 4.2.1. The SPL was evaluated both outside and inside the helmet or headset. Inside the helmet the measuring microphone was always placed in the same spot at the entrance of the ear canal. Exterior noise was measured above the seat belt at shoulder level.

The tape-recorded samples were analysed and averaged over the measurement period of the flight (5 min–2 h) in 1/3 octave bands by a B&K 2131 real-time analyser. The results were summarised for similar plane and helmet/headset types as the means of the SPL values and their SDs.

4.3 Noise exposure of overflights (Study IV)

The test measurements were originally launched because of two civil persons who claimed to have suffered hearing losses after overflights by FiAF jet aircraft.

The measurements of the low-altitude overflights were done using a Hawk BAe MK 51 jet trainer and MIG 21 Bis, Saab 35 Draken and F-18 Hornet jet fighters. All the overflights were done at subsonic speeds at altitudes of 50 and 300 m above the ground with and without the afterburner (AB) (Hawk, no AB). The fighters flew two similar overflights, and the pilots tried to maintain all parameters as similar as possible in all cases. The presented results are averaged values measured during two overflights/aircraft. There were two measurement points on the ground. The first site was situated right below the flight path at a height of 1.6 m above the ground. The second measurement site was situ-
ated 90 m to the side of the flight track with a 10x5 m vertical wall of an aircraft shelter at a distance of 18 m behind the site.

The noise was measured at the first measurement point by a B&K 2209 precision impulse sound level meter which was equipped with a B&K 4136 condenser microphone, and the signal was tape-recorded by a DAT recorder (Sony TCD-D7, Sony, Tokyo, Japan). At the second measurement point the noise was measured by an integrating sound level meter (MIP 7178P, MIP Electronics Oy; Kerava, Finland), and the signal was tape-recorded by a Sony TCD-D8 DAT recorder. The tape-recorded signals were analysed in the laboratory using an FFT analyser (Advantest R9211B, Advantest Corporation, Tokyo, Japan), a B&K 2131 real-time analyser, a B&K 2209 sound level meter and a B&K 2307 recorder. Time and frequency analyses, peak levels and maximum levels were measured, and from the time analysis exposure levels (L_{Aeq, 1s} or L_{Aeq, 8h}) were determined. The exposure level is also called the ASEL-value, which means an A-weighted exposure level of over 1 second.

The two subjects who claimed NIHL after the overflight by the FiAF jets are described in the following:

Subject 1. A Mig 21 Bis flew near a male (born in 1934) who was fishing on the ice in the Kallavesi Lake area and the fighter took up sharply near him. At the left side there was a cliff wall where from the sound was reflected to the left ear, causing dullness and tinnitus. The next day Subject 1 visited a physician at the nearest health care centre and on the second day a flight surgeon at the nearest air base. According to examinations, there was acute hearing damage in the left ear. According to the flight squadron information, the aircraft flew at an altitude of more than 300 m all the time and without the AB.

Subject 2. A Hawk jet trainer flew at low altitude over Subject 2 (female, born in 1936) while she was walking in the wilderness in Lapland. Instantly, the right ear which was towards the noise reacted with dullness and tinnitus. Subject 2 also experienced mild dizziness. Having returned from the trip, the person visited an ENT specialist. According to these examinations, she had acute hearing damage in her right ear. Tinnitus persisted at least a half year after the event.

4.4 Temporary Threshold Shift (Study V)

A total of 51 subjects, pilots and other crew members from the FiAF, were tested. The age of the test persons varied from 19 to 48, with a mean age of 28.2 and a median age of 25.9 years. One test subject was a female and the rest were males. The subjects wore their individually fitted helmets with no additional protection in the ear canal. During the day of the test a baseline audiometry was taken with a noise-free period of at least 14 hours. The tests were administered in the squadrons where the pilots carried out preparations for their flights, which enabled flexible examinations and ensured a minimum of delay between the exposure and post-exposure hearing measurements. The flights were normal missions at four bases.

Otoscopy was carried out before the audiometry on the testing day. Hearing thresholds were measured in a sound-proof chamber (CA Tegner T-bur, Sweden) using a clinical audiometer (Madsen Orbiter 922, Madsen Electronics, Denmark). TDH 39 headphones
with MX-41/AR cushions and HF Koss HV /1A (Koss, Milwaukee, Wi, USA) head-
phones were used for the frequency ranges of 0.125 to 8 kHz and 8 to 20 kHz, respec-
tively. The post-flight measurements were done as soon as possible after each flight in
order to study the TTS. Measurements could be started after approximately 20 to 40 min-
utes had elapsed from the cessation of noise exposure, with each measurement lasting
about 20 minutes. An ascending-descending technique in 5 dB steps was used
(ISO 8253-1 1989). The same method was used for EHF audiometry.

Measurements of noise doses and for continuous time and frequency analyses were
carried out and analysed as described earlier in Chapter 4.2.1.

The noise exposure tests were conducted on a British Aerospace Hawk BAe MK 51
advanced jet trainer and on Saab 35 Draken, Mikoyan & Gurevich Mig 21 Bis and Boe-
ing F-18 Hornet interceptors. Because of its noisiness, a turboprop-powered Valmet Re-
digo liaison aircraft was also included.

Estimates for the average temporary th reshold shift were made using SAS® Proprie-
tary Software Release 8.2 (TS2M0) and a mixed procedure (SAS Institute Inc., 2000). A
mixed model for repeated measures was used because measurements from the same indi-
viduals could not be considered as independent. Therefore, the covariance matrix for av-
erage TTS-estimates had to be estimated. An unstructured covariance structure was used,
although a compound symmetry structure gave almost as good a model fit to data accord-
ing Schwarz’s Bayesian Information Criterion (SBIC). A maximum likelihood algorithm
was used to estimate the covariance parameters. A standard test for equality of propor-
tions was also used.

4.5 Permanent threshold shift and assessment of hearing loss risk
(Study VI)

For the NoiseScan database, which was used for the risk evaluation and data collecting
method, a special questionnaire was used to gather data on the pilots. The questionnaire
included military noise data, like flight hours, firing, explosions and also leisure-time
activities. In addition, data on diseases, hereditary hearing problems, smoking, use of
drugs, serum cholesterol and blood pressure were collected. The results of hearing
threshold measurements conducted as part of the pilot selection process were used as a
reference audiogram. Since annual medical examinations include measurement of blood
cholesterol, blood pressure, and hearing thresholds, data on these variables was readily
available. The data was entered into the NoiseScan database (Starck et al. 1999a, Pyykkö
et al. 2000).

The data was transferred from the NoiseScan software into SPSS 9.1 (SPSS Inc, Chi-
cago, USA) statistical software for statistical analysis. The significance of the relations-
ships between variables in the raw data was evaluated using the Pearson linear correlation
coefficient. Kendall’s correlation coefficient was calculated for categorical variables.
4.5.1 Hearing levels

The subjects of the measurements consisted of 281 male military pilots who flew missions on aircraft types operated by the FiAF. Their average age was 31 years (range 20 to 51 years). Seven pilots were excluded due to incomplete data, and the results are from 274 pilots. A clinical examination of the ear, nose, and throat of each subject was carried out before the audiometry on the testing day. Hearing thresholds were measured in a sound-proof chamber (CA Tegner AB, T-bur, Sweden) using a clinical audiometer (Saico Model SC 6, Interacoustics, Assens A/S, Denmark) with TDH 39 headphones and MX-41/AR cushions at frequencies from 0.125 to 8 kHz. The measurements were carried out using an ascending-descending technique in 5 dB steps (ISO 8253-1 1989).

4.5.2 Noise Exposure Assessment

For the NoiseScan database, aviation noise exposure levels were measured according to the measurements and methods described in Chapters 4.2 and 4.4.

In addition, exposure levels of the cockpits and at the ear entrance of the pilots were available from the older aircraft, which were no longer in operational use by the FiAF (Starck & Kuronen 1990). Measurement for continuous time and frequency analyses was done in a Fouga Magister jet trainer, Hughes 500 and MI-8 helicopters and a DC 3 aircraft, using a two-channel recorder (Nagra, Kudelski S.A., Cheseaux, Switzerland) and miniature microphones (Knowles ME 3046, Knowles Inc, Itasca, Illinois, USA) (Starck & Kuronen 1990). The data was analysed using a B&K 2031 FFT analyser.

4.5.3 Other Risk Factors

In order to determine the risk of noise induced hearing loss, an individual risk index was calculated for each pilot. The number of health risk factors in this study was four: smoking, use of pain killers, blood pressure and serum cholesterol. The risk index increased by one if an individual had one of these risk factors. Thus, the number of risk factors varied between zero and four. The cut-off values were 132 mm Hg for systolic blood pressure, 90 mm Hg for diastolic blood pressure, and 5.7 mmol/l for serum cholesterol.
5 Results and comments

5.1 Laboratory noise attenuation abilities of protection devices used in military aviation (Studies I, III)

5.1.1 Helmets

Helmet comparison in the laboratory. The attenuation provided by air crew helmets varied from 10 to 21 dB(A) in the laboratory (Table 1). At frequencies of less than 1 kHz, the Alpha helmet was the best attenuator (7–33 dB), and the ZSH-5 helmet was the poorest (-2 to 15 dB). In the frequency range of 1–8 kHz, the Swedish FFV 113B flyghjälm was the best, but the differences between the helmets were typically less than 10 dB. The Gentex ACS helmet did not attenuate as well as the other helmets in this frequency range, but it was not personally adjusted. Therefore, the comparison is somewhat unfair. This situation was also apparent from the standard deviation of the ACS helmet in which the noise was significantly higher than for the other helmets. Therefore, the ACS helmet represented an unadjusted aviation helmet in this study. For the Alpha helmets the standard deviation was less than 5 dB, and for the ACS it was about 15 dB.

When the A-weighted attenuation values were compared, the following values were determined for the protectors: 22 dB for the Alpha helmet, 21 dB for the FFV helmet, 16 dB for the unadjusted ACS helmet, and 10 dB for the ZSH-5 helmet.
Table 1. Measured attenuation values for helmets under laboratory conditions. Values are means of measured attenuations (standard deviation) in decibels, n = number of subjects, ANC = active noise cancellation

<table>
<thead>
<tr>
<th>Protector</th>
<th>Mean Attenuation and (Standard Deviation), dB 1/3-octave Band Frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63</td>
</tr>
<tr>
<td>Alpha Helmet (n = 13)</td>
<td>7.5</td>
</tr>
<tr>
<td>Alpha + sunglasses Zeiss (n = 9)</td>
<td>1.8</td>
</tr>
<tr>
<td>Alpha + sunglasses Zeiss (n = 13) repetition test</td>
<td>3.0</td>
</tr>
<tr>
<td>Alpha + sunglasses Randolph (n = 9)</td>
<td>1.4</td>
</tr>
<tr>
<td>Alpha + cushion cloth (n = 9)</td>
<td>6.3</td>
</tr>
<tr>
<td>Alpha ANC (n = 11)</td>
<td>10.7</td>
</tr>
<tr>
<td>FFV 113B/DK (n = 11)</td>
<td>3.5</td>
</tr>
<tr>
<td>ZSH-5/MG (n = 10)</td>
<td>0.9</td>
</tr>
<tr>
<td>ACS (unadjusted) (n = 5)</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Comment. For aviation helmets and other noise helmets, personal adjustment is important. Incomplete adjustment results in poorer attenuation, and the difference in standard deviation increases. The differences between Alpha and ACS could partly be explained by the low number of test persons (13 subjects for the Alpha and 5 subjects for the ACS), but personal adjustment is another parameter.

Probably the material and light structure of the ZSH is one reason for the poorer attenuation, however, these parameters were not compared with other helmets. The pilots usually liked to have this helmet type because of its comfortableness. It has not been used in the FiAF in other aircraft types except the Russian Mig.

During the flight A-weighted noise levels varied between 80 and 105 dB(A) in the cockpits of the fighters and helicopters; therefore, to achieve an A-weighted noise level of less than 85 dB in the ear of the pilot, the noise attenuation of the helmets should generally exceed 20 dB over the audible frequency range. These attenuation values were reached by all the other tested helmets and earmuffs except the ACS and ZSH-5. It is possible that the ACS helmets could have achieved this level of attenuation after personal adjustment by the pilots, but for the ZSH-5 helmet thorough structural changes would be needed.

In this study A-weighting was used as a comparison parameter between different hearing protectors. However, A-weighting should be used only in actual circumstances against real aircraft noise. If the noise is of low frequency, as in propeller blade planes,
then the A-weighted attenuation of helmets and headsets can be less than 15 dB for all the tested protectors, but if the noise is of medium or high frequency, then the A-weighted noise attenuation can be 15–30 dB, depending on the frequency spectrum of the noise source. In practice, the real situation is complicated and this analysis is also confused by communication noise, which creates a significantly varying sound level in the time domain.

At low frequencies (less than 1 kHz) the aviation helmets did not attenuate as well as the headsets or muff-type hearing protectors, probably due to the lack of an effective spring tension in the cup. In the design of aviation helmets it is difficult to incorporate flexible and reliable spring tensioning of the cup against the head of the helmet user. On the other hand, at high frequencies (over 1 kHz), the helmets attenuated better than the headsets or hearing protectors because less bone conduction probably occurred than with the headsets. The helmets protect the skull better than the headsets and also hinder the skull vibrations, thereby, decreasing bone conduction. Therefore, if the best noise attenuation of the whole frequency range is sought, one should combine the good properties of the helmets and headsets (Pääkkönen & Tikkanen 1991).

The insertion loss method (Berger 1986) used to compare the helmets and headsets is one practical method for analysing the noise attenuation of helmets and headsets. There are also many other standardised methods, such as the subjective method and the use of an artificial head. Berger (1986) has reviewed the different methods used to measure the transfer function of the open ear (ISO 4869-3 1989, ISO 4869-1 1990). However, in this study, the noise insertion method was used because a similar measurement method was that time used in the United States for actual noise exposure inside and outside the noise helmet or headset of pilots.

The microphone cord effect was proved to be +/-2 dB at frequencies 1–4 kHz but at low frequencies (< 500 Hz) there was practically no difference (Pääkkönen et al. 1991).

The results of the laboratory measurements can be estimated to present better attenuation levels than in real working conditions. However, they present the results of the individually adjusted helmets that the pilots use during missions. Therefore, the results are base values which can be compared to the results of real missions.

**Sunglasses and cloth covering of earcups.** In the frequency range below 0.25 kHz, the thin cloth over the flight helmet’s cushion that makes the plastic cushion more comfortable made attenuation 1–3 dB poorer than without the extra cloth. In the range of 3.2–4 kHz the cloth worsened attenuation by 3–5 dB and at other frequencies, by 1–2 dB. With sunglasses (specified Zeiss frames for military aviation), attenuation is 4–6 dB poorer below the 0.25 kHz frequency range. In the frequency range of 6.3–8 kHz attenuation with the sunglasses was 3–4 dB poorer. In other frequency ranges the sunglasses had a 1–2 dB weakening effect on the average attenuation values, but for some subjects the use of sunglasses deteriorated the attenuation properties of the aviation helmets significantly.

**Comment.** The headset leakage measured by the insertion-gain method showed that leakage due to the glasses was primarily in the low-frequency region below 1 kHz (Wagstaff et al. 1996). The masking effect of this extra noise may cause aircrew to turn up the radio volume to increase signal intensity, thereby increasing radio noise. Wagstaff et al. (1996) noticed that speech intelligibility may decrease significantly when glasses were used. Prevention of leakage is difficult when using glasses. Headsets and glasses
should be carefully fitted. Although they are very expensive, using corrective visors instead of glasses might, however, might be a solution when a helmet is used.

5.1.2 Headsets and earmuffs

When the A-weighted attenuation values were compared, the best attenuation value 31 dB was achieved with the Silenta Super earmuff, and 27 dB with the Ampliguard headset. For the headsets and earmuffs, the standard deviations of the tests were typically less than 5 dB over the whole measured frequency range (Table 2).

The Silenta Super earmuffs were typically better over all the tested frequencies when the earmuffs (Silenta Super) and the headset (Ampliguard) were compared. In the range of 0.5–3 kHz, Silenta was approximately 4–7 dB better. However, when the Alpha aviation helmet and the Silenta Super earmuffs were compared, the aviation helmet was better in the frequency range of 3.2–8 kHz. The difference in attenuation was less than 5 dB at these frequencies. The difference in noise attenuation between a new and a used headset (Ampliguard) was less than 5 dB.

Table 2. Measured attenuation values for headsets and protectors in laboratory. Values are means of measured attenuations (standard deviation) in decibels, \( n = \) number of subjects

<table>
<thead>
<tr>
<th>Protection</th>
<th>Attenuation, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/3-octave Band Frequency,Hz</td>
<td></td>
</tr>
<tr>
<td>63</td>
<td>125</td>
</tr>
<tr>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>1k</td>
<td>2k</td>
</tr>
<tr>
<td>3k</td>
<td>4k</td>
</tr>
<tr>
<td>6k</td>
<td>8k</td>
</tr>
<tr>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

| Ampliguard 3320 Headset       | 6.4 (1.8)       |
| new (\( n = 13 \))            | (2.1)           |
| Ampliguard 3320 Headset       | 6.3 (2.0)       |
| new, repetition Test (\( n = 9 \)) | (1.8) |
| Ampliguard 3320 Headset       | 5.2 (2.7)       |
| used headset (\( n = 9 \))     | (1.4)           |
| Silenta Super Muffs (\( n = 13 \)) | (2.4) |
| (new)                         | (2.2)           |
| (new, repetition Test)         | (1.3)           |
| (used)                        | (2.1)           |

**Comment.** Ampliguard headsets are equipped with aviation communication technology, which may influence the structure, which is more complicated than the structure of a pure protector, as the Silenta Super, which provides better attenuation.

The results indicate that the Silenta Super provided protection which is sufficient in aviation noise experienced by platform workers in the FiAF. The protectors have to be otherwise in good condition and properly fitted. The test conditions were excellent in the anechoic chamber and the standard deviation is small. Ampliguard is seldom used as a pure protector because it is intended to be the communication device in an aircraft.

If one estimates that a Silenta Super earmuff can reduce fighter noise by 30 dB, the daily exposure of maintenance technicians varies between 63–67 dB, and if the A-weighted instantaneous sound pressure levels vary between 110–120 dB, then the maximum noise levels entering the ear canal would be 80–90 dB.
5.1.3 Active noise cancellation

The ANC devices were measured under laboratory conditions and during real working conditions. When the ANC protectors were compared in the noise-proof chamber, the attenuation of the protectors deviated significantly. The active noise cancellation had a clear effect in the very low frequency range of 0.063–0.5 kHz, where the attenuation was improved by 3–19 dB (Figure 2). Otherwise it functioned like a normal helmet system. The Sennheiser ANC headset reduced noise even at frequencies of less than 30 Hz, the point at which the other protectors started to attenuate. The Sennheiser protector was clearly the best at all the measured frequencies, whereas the attenuation results of other protectors varied. Therefore, it is difficult to comment on the ranking order of the other three protectors. The noise attenuation in the frequency band of 0.125 kHz was 12 dB (average SD 2) with the Gentex helmet/Bose ANC device, 20 dB (SD 1) with the Racal headset, 26 dB (SD 4) with the Alpha helmet/Alpha ANC device and 31 (SD 1) with the Sennheiser headset.

Fig. 2. An example of attenuation when using the Alpha helmet with and without the active noise cancellation (ANC) system.

Comment. The tested ANC system did not always work properly in the first tests, and therefore the pilots did not always like to use it. This was noticed as subjectively harmful acoustic feedback in our first laboratory tests. The ANC system was vulnerable when the position of the helmet changed or when the power from the battery weakened (Pääkkönen & Kuronen 1996). The reliability and technical solutions have been improved at the end of 1990s. According to the present results, the best effect would be attained by an aviation helmet (for bone conduction improvement) with an ANC system and high quality earcups (for passive noise attenuation). This kind of solution should also improve speech intelligibility. There are number of factors which should be taken into account before implementing the ANC system into operational use in the aircraft. It seems that according to general information from various scientific meetings, ANC is coming into operational use in helicopters and, e.g., in the new U.S. Air Force F-22 Raptor fighter.
5.2 Flight noise exposure and personal protection during flight operations (Studies II–III)

The noise levels were measured by microphones in real working conditions outside the hearing protectors or helmets and at the ear entrance. The averaged noise values ($L_{Aeq}$ dB) for the pilots in military jet aircraft varied in the cockpit from 97 dB to 106 dB and at the ear entrance from 86 dB to 99 dB. The highest values were measured in the Fouga Magister jet trainer. The technicians received similar noise exposure varying from 93 to 97 dB. The start values were the highest at 108 dB ($L_{Aeq 15 \text{ min}}$) for Hornet and Hawk aircraft, which also use an auxiliary starting motor. The values are presented in Table 3.
Table 3. Aircraft type, number of pilots, cabin noise, noise at the entrance of the ear canal, difference in the noise between the cabin and the entrance of the ear canal (communication noise included), noise inside the helmet due to aircraft noise (communication noise excluded), and attenuation offered by the hearing protector, helmet and headset type, by aircraft.

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Cabin noise (L_{Aeq}, dB)</th>
<th>Noise at ear entrance (L_{Aeq}, dB)</th>
<th>Difference between cabin and ear entrance noise (L_{Aeq}, dB)</th>
<th>Noise through protection (L_{Aeq}, dB)</th>
<th>Attenuation (L_{Aeq}, dB)</th>
<th>Helmet or headset type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fighters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saab 35 Draken</td>
<td>102</td>
<td>86</td>
<td>16</td>
<td>82</td>
<td>20</td>
<td>FFV Flyghjälm, Sweden</td>
</tr>
<tr>
<td>Mig 21 Bis</td>
<td>104</td>
<td>98</td>
<td>6</td>
<td>94</td>
<td>10</td>
<td>ZSH-5A, Russia</td>
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<tr>
<td>Hornet F-18</td>
<td>97</td>
<td>89</td>
<td>8</td>
<td>80</td>
<td>17</td>
<td>Gentex, USA</td>
</tr>
<tr>
<td>Jet trainers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fouga Magister</td>
<td>106</td>
<td>99</td>
<td>+7</td>
<td>82</td>
<td>24</td>
<td>HGU-2, Sierra Inc., USA</td>
</tr>
<tr>
<td>Hawk BAe 51 MK</td>
<td>100</td>
<td>92</td>
<td>8</td>
<td>83</td>
<td>17</td>
<td>Alpha Series 300, Helmets Integrated, UK</td>
</tr>
<tr>
<td>Helicopters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hughes 500</td>
<td>110</td>
<td>98</td>
<td>+12</td>
<td>83</td>
<td>27</td>
<td>Alpha Series 200, Helmets Integrated, UK</td>
</tr>
<tr>
<td>MI-8</td>
<td>88</td>
<td>90</td>
<td>-2</td>
<td>69</td>
<td>19</td>
<td>Alpha Series 200, Helmets Integrated, UK</td>
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<td>Transports</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DC 3</td>
<td>101</td>
<td>100</td>
<td>+1</td>
<td>97</td>
<td>4</td>
<td>E 332, Amplifox, UK</td>
</tr>
<tr>
<td>Fokker Friendship</td>
<td>88</td>
<td>84</td>
<td>+4</td>
<td>77</td>
<td>11</td>
<td>Peltor 3002, Sweden</td>
</tr>
<tr>
<td>Other aircraft</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Learjet</td>
<td>83</td>
<td>83</td>
<td>0</td>
<td>72</td>
<td>11</td>
<td>Peltor 3002, Sweden</td>
</tr>
<tr>
<td>Piper Arrow</td>
<td>95</td>
<td>95</td>
<td>0</td>
<td>92</td>
<td>3</td>
<td>E 3320, Amplifox, UK</td>
</tr>
<tr>
<td>Valmet Vinka</td>
<td>97</td>
<td>97</td>
<td>-3</td>
<td>89</td>
<td>8</td>
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</tr>
<tr>
<td>Valmet Redigo</td>
<td>100</td>
<td>91</td>
<td>9</td>
<td>88</td>
<td>12</td>
<td>Alpha Series 300, UK</td>
</tr>
</tbody>
</table>
5.2.1 Attenuation of helmets

Figure 3 shows examples of time analysis and figure 4 shows examples of frequency analysis, where instantaneous noise levels are shown also in the cockpit and inside the helmet at the entrance of the ear canal.

Fig. 3. Examples of time analysis of the noise in the cockpit and inside the flight helmet over a flight.
Fig. 4. Examples of frequency analysis of the noise in the cockpit and inside the flight helmet during flight.

The speech communication signal noise (the difference compared to basic noise is 20–30 dB) can be seen as a large variation in noise levels near the ear canals. At very low frequencies (less than 0.1 kHz) the noise level is higher inside the helmet than outside. At other frequencies (0.2–10 kHz) the noise attenuation was 5–25 dB, depending on the fighter, the helmet and the amount of communication during the flight sortie.

Table 4. Analysis of radio noise and background noise based on helmet and headset attenuation and of the difference in noise and the radio noise in the time and frequency analyses.

<table>
<thead>
<tr>
<th>Plane</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hornet F-18 (n = 3)</td>
<td>99</td>
<td>19</td>
<td>80</td>
<td>90</td>
<td>84</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Draken 35 (n = 1)</td>
<td>102</td>
<td>21</td>
<td>81</td>
<td>90</td>
<td>85</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Mig 21 Bis (n = 7)</td>
<td>104</td>
<td>10</td>
<td>94</td>
<td>98</td>
<td>94</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Hawk BAE MK 51 (n = 4)</td>
<td>102</td>
<td>22</td>
<td>80</td>
<td>90</td>
<td>85</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Redigo (n = 2)</td>
<td>101</td>
<td>22</td>
<td>79</td>
<td>89</td>
<td>88</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Piper Cherokee (n = 2)</td>
<td>92</td>
<td>-</td>
<td>-</td>
<td>86</td>
<td>82</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Piper Chieftain (n = 2)</td>
<td>92</td>
<td>-</td>
<td>-</td>
<td>83</td>
<td>77</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Fokker Friendship (n = 2)</td>
<td>85</td>
<td>-</td>
<td>-</td>
<td>74</td>
<td>73</td>
<td>-</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4 shows a summary of the results of measurements based on time and frequency analyses for the pilots’ exposure. The measured cockpit noise levels are shown in the column 1. The attenuation values from laboratory measurements are shown in the column 2. The values in the column 3 show the best calculated noise levels inside the helmets. The
values of the column 4 show the measured values from the microphones which were installed at the entrance of the ear canal. The values of the column 5 present the measured noise without radio noise. The values of the column 6 show the noise difference between calculated and real situation. The values of the column 7 show how much the radio noise increases the background noise inside the helmet. So, the Table 4 includes measurements of radio noise and cockpit noise inside the helmet, and these analyses seem to indicate that the radio noise is on average 4–10 dB higher than the background noise inside the helmet when measured as equivalent noise. The sudden noise level difference was significantly higher, 10–20 dB, as shown in Figure 3. If the increasing effect of the aircraft radio is excluded, using the noise dose measurements and the measured values for helmet attenuation, the difference between the cockpit and the ear canal was 10–13 dB for the Hornet, Draken and Hawk and 5 dB for the Mig.

Comment. Pilots are exposed to a noisy environment when moving on the platform and during missions. If a pilot flies four flights or sorties daily, then the daily A-weighted equivalent level (L_{Aeq 8h}) varies from 85–92 dB, depending on the aircraft type. These levels suggest a risk to hearing. If the cockpit noise penetration into the helmet is considered, the equivalent noise levels varied from 80–94 dB. Of the fighters in this study, the Mig 21 Bis had the highest cockpit noise levels and at the same time the poorest flight helmet noise attenuation. Therefore, in this aircraft the noise level inside the helmet during the flight was more than 10 dB higher than in the other fighters. Obviously, this was why many pilots also used earplugs in the Migs. However, the typical missions for Migs were 30–40 minutes and the total fighter noise exposure during the pilot’s career (seldom more than 1000 flight hours by Migs) has not been very high. According to the equal energy rule, the noise exposure of 91 dB should not exceed 2 hours and respectively, 94 dB exposure should not exceed 1 hour.

Radio communication also increases the noise exposure of the pilot. The speech intelligibility of radio communication is a significant safety factor, and in order to improve speech intelligibility one should minimise cockpit noise to a minimum and also improve the noise attenuation of flight helmets and headsets to a maximum. These measures could allow some reduction of the volume of radio communication (Wagstaff et al. 1999, Wagstaff & Woxen 2001). Analyses of the frequency spectra show indirectly that that the most important noise frequency range inside the helmet is from 0.3 to 3 kHz which results mostly from the speech frequencies influencing on these frequencies.

In real conditions, the pilots are moving their head continuously in the cockpit when looking out the environment, probably the movements are increasing also noise leakages. At very low frequencies the noise level inside the helmet is higher than in the cockpit. This effect is known as the occlusion noise effect (Berger 1986), and it can be improved by using an active noise cancellation technique. Besides, the helmet resonance phenomenon might also increase low frequencies inside the helmet.

Concerning the risk of NIHL in the FiAF, we have to approximate the total exposure according to flight hours. At the end of a pilot’s flight career in Finland (1000–3000 flying hours), he approaches the level of exposure at which, when compared to other studies (Ribak et al. 1985, Fitzpatrick 1988), the risk of hearing loss starts to emerge. Based on this estimation, if the pilots are only exposed to flight noise of their own, the risk of hearing loss does not appear to be significant. Therefore, flight safety parameters seem to be more important in instant evaluation of noise effects on pilots.
The analyses of frequency spectra versus time indicated indirectly that for radio communication the most important frequency area is 0.3–3 kHz. Thus the helmet should attenuate this frequency area as much as possible. If the flight helmets are compared to a specially developed noise helmet (Pääkkönen et al. 1991), there are also development possibilities in classical noise enclosing principles, especially at frequencies over 0.5 kHz. However, flight helmets are very special products and the attenuation of noise is only one aspect of the whole specification. Therefore, it is not possible to take maximal noise attenuation properties into account in the design.

5.2.2 Attenuation of headsets and earmuffs

The noise levels of the maintenance technicians in working conditions were measured by using the microphones outside the hearing protectors and at the ear entrance. The noise exposure (L_{Aeq}) of technicians on the platform varied from 93 to 97 dB. Attenuation measured while working was as high as 30 dB(A) for the Silenta Super earmuffs, so Silenta Super earmuffs attenuated this noise exposure to the level of 70–80 dB.

Comment. The noise levels to which maintenance technicians on the platform are exposed are high enough to cause NIHL. The Silenta Super protector should give enough protection to prevent NIHL. However, it is always possible that the hearing protectors have defects or they are not worn properly, creating a risk of leakage. In intense flight operations at the air base, the noise exposure of technicians and land officers is probably even higher than during a routine day. Communication is usually done by hand signals, but there would be a need to include reliable radio communication between the people on the platform and in the aircraft.

5.2.3 Noise attenuation provided by active noise cancellation

The ANC devices were measured during the flight missions. The Redigo liaison aircraft had the highest noise levels. The ANC protectors were compared during the Redigo flight, and the attenuation values can be seen in Figure 5. The presented values are averages of four test persons, and the effect of the ANC system can be seen in the frequency range of 0.01–0.5 kHz. The best attenuation was attained with the Sennheiser headset system. For example, in the frequency band of 0.125 kHz, the difference could be as great as 28 dB between it and the passive and active systems, and as much as 16 dB between it and the helmets’ ANC systems. In addition, all the test persons preferred the Sennheiser system for its noise attenuation and comfort properties. The measured A-levels inside the ANC protectors varied from 79 dB for the Gentex helmet/Bose ANC device, 78 dB for the Alpha helmet/Alpha ANC device, 78 dB for the Racal headset, to 70 dB for the Sennheiser headset.
Fig. 5. Active noise cancellation during the Redigo flight. Average values of four test subjects with different systems (Gentex helmet/no ANC, Gentex helmet/Bose ANC, Sennheiser headset, Racal headset, Alpha helmet/Alpha ANC).

In the Fokker Friendship, a two-engine turbine propeller aircraft, the A-weighted SPL at the wing level was 71 dB inside the Gentex/Bose helmet and 65 dB inside the Sennheiser headset. The blade frequencies were clearly attenuated by the ANC system.

All the active noise systems worked properly under the measurement conditions of this study. No severe acoustic feedback effects caused by ANC were found. When the attenuation results obtained in the aircraft and the low-frequency chamber (the exposing noise was relatively similar) were compared, the attenuation results were relatively similar in the frequency range of 0.063–1 kHz. In the frequency range of 0.008–0.063 kHz the attenuation values were modest and only the Sennheiser headset could provide real attenuation when the ANC mode was on. In this low-frequency range (0.008–0.063 kHz) the noise exposure levels in both aircraft and the low-frequency chamber was so high that the occlusion effect did not affect the results significantly. In the frequency range of 1–8 kHz (measured only in the Redigo aircraft), the aviation helmets attenuated better than the headsets because the helmets can also attenuate bone conduction. The communication properties of the studied headsets and helmets were not measured in the tests.

Comment. The main purpose for active noise reduction is to improve the attenuation of lower frequencies, and therefore the solution might also improve speech intelligibility. (Wagstaff et al. 1998). At frequencies of 0.08–0.16 kHz noise attenuation varies between 5 and 15 dB for headsets and between 0 and 10 dB for aviation helmets (Pääkkönen 1992). This frequency range represents a significant area of ANC because ANC can improve significantly the attenuation of headsets and helmets in the frequency range of less than 0.5–1 kHz (Pääkkönen et al. 2001). However, the effect of ANC is not as well known at frequencies under 0.1 kHz. Human speech covers the frequencies of 0.16–6 kHz (ISO TR 4870 1991). In this range, an ANC system can influence the low-frequency spectra of good quality...
speech, especially under conditions found in propeller aircraft and helicopters, where the noise spectrum is of a low frequency. On the other hand, headsets and helmets can attenuate higher frequencies well because of their passive structural properties (Berger 1983, Pääkkönen et al. 1991). Therefore, a combination of ANC and the structural solutions of protection devices is the most efficient way to improve noise attenuation nowadays.

We measured the ANC devices also in the low frequency chamber to get better background for the flight evaluations and to standardise the testing procedures (mainly to avoid head movements). Theoretically, the noise leakages caused by the microphone cord and head movements during the flight tests might influence mainly to the low-frequency response but we did not find it in our measurements. However, the standard deviations seemed to be smaller in the laboratory tests. Comparing the laboratory test results to flight tests is complicated because the aircraft noise levels are continuously fluctuating, therefore, the average noise level is a theoretical concept. Also, the frequency spectras between the laboratory and flight tests were not quite the same.

### 5.3 Noise exposure of overflights (Study IV)

The noise exposures and measurements of overflying military jets were measured at an open airport where the measurement systems were installed. The aircraft flew over at the given altitudes and speeds. A summary of the measurement results is shown in Table 5. The limit values of noise levels for a PTS were considered to be 140 dB as the peak level and 130 dB as the noise exposure level for one second, according to the World Health Organization recommendations (Berglund & Lindvall 1995c). Based on this, the limit value for a PTS is exceeded when heard on open ground only if the flight altitude of the aircraft is less than 100 m and the afterburner (AB) is used. In these conditions, a jet trainer (which has no afterburner) does not reach noise values exceeding the limit values. The peak noise levels of fighters were 142–149 dB with the AB on at a distance of 50 m. The time analysis of a Draken fighter overflight with and without AB can be seen in Figure 6. The duration of the significant sound burst at 50 m is 2–3 s and respectively, according to our measurements at the altitude of 300 m, 5–6 s.

![Fig. 6. Time analysis of a Draken overflight noise burst at 50 m with and without AB.](image-url)
Table 5. Low altitude overflight noise results. Average values of two overflights.

<table>
<thead>
<tr>
<th>Distance m</th>
<th>Power</th>
<th>Peak level</th>
<th>Exposure level</th>
<th>Maximum level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>L_{Cpeak}</td>
<td>L_{Aeq}</td>
<td>L_{Aeq}</td>
</tr>
<tr>
<td></td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
<td>dB</td>
</tr>
<tr>
<td>1. Jet trainer Hawk BAe MK 51</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 Const</td>
<td>109</td>
<td>99</td>
<td>54</td>
<td>93</td>
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<tr>
<td>300 Acc</td>
<td>121</td>
<td>107</td>
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<td>105</td>
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<td>107</td>
<td>62</td>
<td>108</td>
</tr>
<tr>
<td>50 Acc</td>
<td>132</td>
<td>115</td>
<td>70</td>
<td>118</td>
</tr>
<tr>
<td>2. Fighter MIG 21 Bis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 Const</td>
<td>117</td>
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<td>300 AB</td>
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<td>50 AB</td>
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<td>126</td>
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<td>3. Fighter Saab 35 Draken</td>
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<td></td>
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<td></td>
</tr>
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<td>69</td>
<td>109</td>
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<tr>
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<td>50 AB</td>
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<td>124</td>
</tr>
<tr>
<td>4. Fighter F-18 Hornet</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300 Const</td>
<td>126</td>
<td>118</td>
<td>73</td>
<td>110</td>
</tr>
<tr>
<td>300 2xAB</td>
<td>134</td>
<td>125</td>
<td>80</td>
<td>117</td>
</tr>
<tr>
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<td>141</td>
<td>126</td>
<td>81</td>
<td>122</td>
</tr>
<tr>
<td>50 2xAB</td>
<td>149</td>
<td>135</td>
<td>90</td>
<td>132</td>
</tr>
</tbody>
</table>
Fig. 7. Maximum noise spectra of overflight noise ($L_{F\text{max}}$), altitude 50 m, AB on, speed about 0.9Mach.

The figure 7 shows the maximum levels ($L_{F\text{max}}$) of overflights in one-third octave bands. An F-18 Hornet fighter has a higher noise level than the others at both low and high frequencies. In the middle range of frequencies all the fighters are at an almost similar level. The noise energy starts to decrease rapidly when the frequency diminishes below 0.08 kHz, which means there is no significant amount of very low-frequency noise.

Concerning the two cases of people who claimed acute hearing loss after overflight by FiAF jets, only one ear of each subject suffered hearing loss, and according to subjective experiences and examinations the hearing level of the shadowed ear remained unchanged. According to their patient records, both subjects complained of dullness and tinnitus in the damaged ear. According to the audiometric examinations, the PTS level covered the whole measured frequency spectrum (0.25–8.0 kHz), and for the both subjects it was roughly 60 dB.

Comment. Reports on the effects of low-altitude overflight noise in the literature on the permanent threshold shift (PTS) of the persons were not available. According to international studies, exceeding the peak sound level of ($L_{\text{Cpeak}}$) 140 dB is most often considered to be harmful to hearing (EEC 89/686 1989). Lawton and Robinson (1991) determined the risk of a temporary threshold shift (TTS) to be 125–126 dB measured as peak sound levels in low-altitude overflight situations. Time weighting has a significant effect on the noise value (Lawton & Robinson 1991). They recommended that the minimum altitude for low-altitude overflights should be more than 300 m. In these conditions no PTS would exist. The risk of hearing loss is significantly person-related, and therefore in this study the peak sound level limit value was 140 dB.

According to our measurements, the Hawk BAe MK 51 jet trainer caused no noise levels which exceeded $L_{\text{Cpeak}} = 140$ dB. The Mig 21 Bis and Saab 35 Draken fighters exceeded the peak noise limit level only at an altitude of 50 m and when the AB was on.
The F-18 Hornet fighter exceeded the peak noise limit at an altitude of 50 m both when the AB was on or off. Exceeding the peak level of 130 dB could occur only when the flight altitude was lower than 200 m and with the Mig or Draken when using the AB. If, however, the limit value is around 125 dB, as Ising, et al., (1991) proposed for TTS risk based on their experiments, then in practice, the minimum safe flight altitude for listeners on the ground is about 300 m (Ising et al. 1991).

One possibility for the NIHL is that the fighters flew at a lower altitude than they reported, although the altitude was checked by the flight squadron. However, in Finland and elsewhere there are thousands of low-altitude overflights annually and only a few events cause a possible hearing loss. Both subjects were at the age of 57–59 years, but there is no information available on the increased sensitivity of older people to this kind of acute acoustic hearing loss.

The subjects in our report might have the influence of the head shadow effect to protect another ear. The effect is frequency dependent and begins at about 1.5 kHz with minimal attenuation and increases up to 15 dB at 5 kHz (Staab & Lybarger 1994).

According to the exposure measurements, the risk of NIHL should be very minimal, however, possible. Tinnitus is also possible and sometimes a very difficult symptom, however, there are not much data available on this area concerning aviation noise. During air shows, however, ear protection is very recommendable, and simple ear plugs should be made available by the arrangers (Pääkkönen et al. 2003). The level of an aircraft noise can cause community and individual annoyance, which can cause many psychophysical effects (Berglund & Lindvall 1995d).

5.4 Temporary threshold shift (Study V)

The TTS was measured by using a conventional and EHF audiometry before and after a flight. The total number of subjects was 51. The tests were conducted in F-18 Hornet, Saab 35 Draken and Mig 21 Bis fighters and Hawk BAe MK 51 training jets. The equivalent cabin noise levels at the level of the subject’s shoulder (L_{Aeq}), noises at the ear canal entrances during the flight mission and the duration of noise exposure (minutes) were also measured. The equivalent noise levels in the cabin were somewhat below and over 100 dB and approximately 10 dB lower at the ear canal entrance. The peak impulse levels (L_{Cpeak}) of radio communication were usually clearly less than 140 dB for propeller-driven and other aircraft.
Table 6. Estimates of average temporary threshold shifts of conventional audiometry for both ears by frequency.

<table>
<thead>
<tr>
<th>kHz</th>
<th>Ear right</th>
<th>Estimate</th>
<th>95%CI</th>
<th>Ear left</th>
<th>Estimate</th>
<th>95%CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
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<td>1.7</td>
<td>(-0.5–2.7)</td>
<td>2.4</td>
<td>(0.3–3.1)</td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>2.3</td>
<td>2.4</td>
<td>(0.7–3.9)</td>
<td>0.8</td>
<td>(0.1–1.7)</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1.7</td>
<td>1.7</td>
<td>(0.5–2.9)</td>
<td>0.8</td>
<td>(0.5–2.9)</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
<td>0.8</td>
<td>(-1.2–1.2)</td>
<td>1.4</td>
<td>(0.3–2.5)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.1</td>
<td>1.7</td>
<td>(0.1–2.1)</td>
<td>1.7</td>
<td>(0.4–3.0)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.2</td>
<td>3.0</td>
<td>(-0.6–2.4)</td>
<td>1.8</td>
<td>(1.2–4.8)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.9</td>
<td>1.7</td>
<td>(-1.2–2.2)</td>
<td>0.5</td>
<td>(-1.5–2.5)</td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Estimates of average temporary threshold shifts of EHF audiometry for both ears by frequency.

<table>
<thead>
<tr>
<th>kHz</th>
<th>Ear right</th>
<th>Estimate</th>
<th>95%CI</th>
<th>Ear left</th>
<th>Estimate</th>
<th>95%CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>2.2</td>
<td>2.5</td>
<td>(0.7–3.7)</td>
<td>1.6</td>
<td>(1.1–3.9)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.7</td>
<td>1.4</td>
<td>(0.2–3.2)</td>
<td>1.4</td>
<td>(0.3–3.1)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1.6</td>
<td>2.4</td>
<td>(-0.1–3.3)</td>
<td>1.6</td>
<td>(0.9–3.9)</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>1.6</td>
<td>1.9</td>
<td>(0.1–3.1)</td>
<td>1.9</td>
<td>(0.1–3.7)</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>2.7</td>
<td>2.2</td>
<td>(0.9–4.5)</td>
<td>1.6</td>
<td>(0.4–4.0)</td>
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</tr>
<tr>
<td>13</td>
<td>2.7</td>
<td>1.6</td>
<td>(0.3–5.0)</td>
<td>2.3</td>
<td>(0.4–4.2)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.2</td>
<td>1.6</td>
<td>(0.2–4.3)</td>
<td>2.3</td>
<td>(0.4–3.6)</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3.5</td>
<td>1.6</td>
<td>(1.6–4.8)</td>
<td>2.3</td>
<td>(0.5–3.6)</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>2.9</td>
<td>1.7</td>
<td>(1.0–4.8)</td>
<td>1.7</td>
<td>(0.4–3.4)</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>1.5</td>
<td>1.2</td>
<td>(-0.1–3.1)</td>
<td>1.2</td>
<td>(0.5–3.0)</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>1.2</td>
<td>1.6</td>
<td>(-0.5–2.9)</td>
<td>1.6</td>
<td>(0.2–2.9)</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>1.8</td>
<td>0.8</td>
<td>(0.2–3.4)</td>
<td>0.8</td>
<td>(0.4–3.1)</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>2.0</td>
<td>1.6</td>
<td>(0.2–3.7)</td>
<td>1.6</td>
<td>(0.0–3.2)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6 shows the estimates for average TTS within the frequencies 0.125 to 8 kHz and their 95% confidence intervals (CIs) for both ears and for each frequency. A statistically significant TTS was detected in the right ear at the frequencies of 0.25, 0.5, and 2 kHz. In the left ear, statistically significant values of the TTS were discovered at the frequencies of 0.125, 0.25, 0.5, 2, 3, and 4 kHz. Table 7 shows the estimates over all measured EHF frequencies for average TTS and their 95% confidence intervals (CIs) for both ears and for each frequency. A statistically significant TTS was detected in the right ear at the frequencies of 8, 9, 11, 12, 13, 14, 15, 16, 19 and 20 kHz. In the left ear, a statistically significant TTS was found at the frequencies of 8, 10, 11, 12, 14, and 18 kHz.

By conventional audiometry, the statistically significant differences were detected in the right ear during flights in the Redigo, Mig, and Draken, while differences in the left ear were evident during flights in the Redigo, Hawk, and Draken. The TTS findings were
statistically significant for EHF in the right ear with the Hornet and the Draken, and in the left ear with every other aircraft except the Redigo.

Pure-tone thresholds for the frequencies of 4 and 6 kHz were also studied. In this study, a statistically significant TTS was found only after flights with the Redigo, this being in the left ear at the frequency of 4 kHz (CI 0.6–6.4).

The hearing thresholds obtained with conventional audiometry can be regarded as excellent. Before the flight, 30/51 (58.8%) of the pilots could detect even the 20 kHz signal with the right ear, 27/51 (47.1%) with the left ear and after the flight, 22/51 (47.1%) and 20/51 (39.2%), respectively. The change was significant in the right ear (p = 0.011).

Comment. The possible occurrence of a TTS after an actual flight was examined. EHF hearing measurements and research with the aim of determining the effects of aviation-related noise have not been conducted before the present study. The NIHL of military flying is less known than that of industrial noise. It would have been interesting to measure the possible TTS effects of the pilots after the rest period but because of the busy working in the squadrons, it was not possible. Anyway, the annual pilots’ fighter flight hours are generally less than 150 hours, which means long resting time without noise exposure and means more safety to hearing compared to working in industry.

Both conventional and EHF audiometry measurements conducted during this study revealed statistically significant but minor TTS at some frequencies with all aircraft types. On the other hand, the obtained hearing thresholds can be considered excellent.

Although the TTS values obtained statistically differ significantly from zero, these findings are clinically insignificant. A TTS was slightly more frequent in the left ear over the frequency range of 0.125 to 8 kHz, a finding in keeping with the results of (Pirilä et al. 1991). However, at EHF s the shift was more frequent in the right ear. In this kind of small material, this finding may be purely coincidental.

The other exposures during the flight, like low or high ambient partial oxygen pressure, acceleration forces and vibration are practically impossible to distinguish as risk factors of TTS in this kind of test procedure.

5.5 Permanent threshold shift (Study VI)

The hearing thresholds were generally good in the frequency range 0.125–8 kHz. The mean hearing thresholds and standard deviations of 274 pilots are shown in the figure 8. The audiometric threshold findings at the 4 kHz frequency were typically better than 15 dB in all age groups (Figure 8). For both ears, the threshold levels were poorer than in first measurements during the follow-up and correlated very significantly with age and exposure (p < 0.006). The threshold levels for the left ear at 4 kHz also correlated with the number of rounds fired using small-caliber arms (p = 0.02). However, the threshold levels did not correlate with the number of rounds fired with large-caliber arms or with the risk index.
Fig. 8. Mean hearing thresholds (n = 274) and standard deviations over audiometric frequencies (0.125–8 kHz) for the left (×) and right (●) ears.

The results were also used to evaluate the usefulness of the NoiseScan programme in the monitoring of the hearing of military pilots by using audiometric results and possible risk factors like blood pressure, smoking, blood lipids, certain drugs, firing, and age as a database.

In order to assess the risk of hearing impairment among pilots, the ISO 1999 (1990) model was applied at the frequency of 4 kHz, using the ages and exposures of the subjects. In a screened population (Database A, ISO 1999 1990) the observed hearing loss has an expected value in the 50% fractile (22 dB). However, in our population the observed hearing loss was considerably smaller, being 12.7 dB in the left ear and 9.3 dB in the right (Figure 9). These values correspond to the 75 and 83 dB fractiles, respectively.
Fig. 9. Military pilots' (n = 274) permanent thresholds due to noise exposure at a frequency of 4 kHz measured with different fractiles in accordance with ISO 1999. The bold line represents the right ear.

Comment. Noise exposure, hearing protection and general health-related risks of pilots were exceptionally well documented in our material. It is therefore safe to assume that various means of assessing the variables associated with the risk of hearing impairment were more reliable than is usually the case in occupational studies.

ISO 1999 (1990) provides a model for predicting the risk of hearing impairment. The distribution provided by this model for hearing impairment at a frequency of 4 kHz is 60 dB between the 10th and 90th percentiles for an exposure time of 20 years and a noise level of 100 dB. Adjusted for this model, the hearing of the pilots corresponds approximately to the 80th percentile, being 9–13 dB better than the 50th percentile obtained with the ISO 1999 (1990) model. The 50th percentile has been considered to be a good estimate of the hearing threshold level of industrial workers (Pykkö et al. 1986, Starck et al. 1999b, Toppila et al. 2001). Pilots presented fewer risk factors than industrial workers. The risk of hearing impairment among pilots seems to be of the same order of magnitude as for industrial workers with few (zero or one) risk factors (Toppila et al. 2001). The hearing levels of the pilots in the range of 0.125–8 kHz were good.

The NoiseScan model is based on the ISO 1999 (1990) standard. In this model the most probable fractile is defined by the number of risk factors. The 80% fractile gives the best prediction for subjects with 0–1 risk factors, the 50 fractile for subjects with 2–3 risk factors and the 25% fractile for subjects with more than three risk factors. The data of the present study agrees reasonably well with this assumption. This also implies that the equal energy principle and the use of A-weighting can be applied to aircraft noise as well as to industrial noise, which is the noise exposure background of the ISO 1999 model.
Fig. 10. Development of hearing loss at 4 kHz in a standard population according to the ISO 1999 model with 50th percentile compared to the smaller risk of hearing loss of military pilots (n = 274) calculated by the NoiseScan model.

The study also reveals the importance of limiting the number of risk factors in the prevention of hearing impairment. Pilots have fewer risk factors, and their hearing threshold levels are better than in the group with more risk factors, such as high blood cholesterol, high blood pressure, smoking and moderate use of pain killers (Toppila et al. 2000).

Figure 10 shows the difference between the prediction of the ISO 1999 (1990) model A population and the NoiseScan model for military pilots. When the typical noise exposure of military pilots is applied to the general population, the model shows that threshold of the military is better than the hearing threshold of the general population at 4 kHz, and the difference increases with age. The reasons probably are the fewer risk factors, better surveillance, good motivation for hearing protection and a better noise attenuation level in a noisy environment.

The NoiseScan model applies in comparing aviation noise exposure and pilots to industrial noise and industrial workers. To our knowledge, this kind of evaluation of military aviation noise has not been done previously.

The total aviation noise exposure was reasonably low because of the small number of flight hours compared to industrial noise on the basis of the total energy principle. The risk of NIHL caused by aviation noise is low.

In conclusion, the risk of hearing impairment of military pilots remains very low on the basis of the results of this research, where some other risk factors of NIHL besides aviation noise were included and evaluated.
6 General discussion

6.1 Noise exposure and personal protection

The data presented here is significant for evaluation of aviation noise exposure and for the present noise protection procedures of pilots in the FiAF. The database of the information concerning the laboratory and audiometry results of the military pilots has been reliably measured and filed. The methods for collecting noise exposure data by attaching miniature microphones to DAT tape recorders, as described here, are well suited for measuring the individual exposure of the pilots. Alternatively, a microphone installed in the ear canal might give even more reliable results of the exposure, including an occlusion effect. However, for flight safety reasons, it is not reasonable to measure noise levels in a microphone in the ear canal during a real mission.

The most important way to evaluate the real risk of NIHL is to measure noise exposure during real working conditions. As pointed out in many studies, laboratory findings probably give too favourable information about the attenuation properties of the different protection devices. However, the laboratory measurements are necessary as base results and also to test a method.

The most reasonable way to report the exposure results is by means of A-weighted noise levels according to the Finnish recommendations. It is also possible to use B and C-weighted levels. The frequency patterns should be measured for the evaluation of the noise profile.

The noise exposure and protection properties should always be measured both in the laboratory and under real conditions when new equipment and aircraft types are taken into operational use in the FiAF. The best time would be during the evaluation phase of the equipment and aircraft.
6.1.1 Helmets and headsets

If the noise is of low frequency type, as in propeller-driven planes, then the A-weighted attenuation of helmets and headsets can be less than 15 dB for all the tested protectors, but if the noise is of mid or high frequency, the A-weighted noise attenuation can be 15–30 dB, depending on the frequency spectrum of the noise source.

The helmet should always be adjusted carefully to fit the anatomic characteristics of the user and to prevent leakage of noise into the ears.

How can we improve the sound environment of the technical personnel around the aircraft during operations? The technical design of the communication properties of the earmuffs and microphones should be developed to allow continuous communication between other maintenance people and pilots. This must be the goal of development, because of operational requirements which will be emphasised in the future when the FiAF fighters operate in English and with foreign co-operators.

6.1.2 Active noise cancellation

When the attenuation results obtained in the aircraft and in the noise-proof chamber (the exposing noise was almost similar) were compared, the attenuation results were relatively similar in the frequency range of 0.063–1 kHz. In the frequency range of 0.008–0.063 kHz the attenuation abilities were modest and only the Sennheiser headset could provide real attenuation in that range when the ANC mode was on. In this low-frequency range (0.008–0.063 kHz) the exposing noise in both the aircraft and the low-frequency chamber was so high that the occlusion effect did not affect the results significantly (Pääkkönen & Tikkanen 1991).

The use of an ANC will be a reasonable solution and which should be evaluated for future helicopters, but it is questionable to implement the system for the present F-18 Hornet and Hawk jets in the FiAF.

6.2 Exposure of overflights (Study IV)

The risk of acute hearing loss because of military jets’ overflight is probably minimal if the distance of an jet aircraft is more than 300 m. ABs, which produce extra thrust, are not usually used during cruising missions, and only low-altitude show missions result in a lot of noisy flying with the AB in use. However, in certain conditions for sensitive persons, the risk of NIHL must be considered after low-altitude jet overflight. Tinnitus, which is a symptom often gaining too little attention, may be another real health hazard besides of the hearing damage.

The disturbing effect and annoyance of overflight noise is a separate area of research. In Finland, the noise exposure over fur animal farms and reindeer herding areas has caused concern, and has therefore resulted in restrictions in the flight activities of the FiAF, especially during the reproductive season. The measurements and evaluations of
community noise are continually under consideration and discussion in Finland, nowadays.

6.3 Temporary threshold shift (Study V)

The hearing thresholds measured using conventional and EHF audiometry were extremely good. In fact, for EHF they were better than, for example, in an earlier Finnish study (Löppönen et al. 1991).

The reasons for the good hearing thresholds might be that the technical solutions of noise protection are typically modern in the FiAF. Flight safety issues, including noise protection, are well adopted by the pilots. Also, noise doses encountered during the flights are relatively small. The measured peak levels of radio communication noise should not increase the risk of hearing damage or a TTS.

It has been shown that at ground-level conditions, breathing 90% oxygen during noise exposure reduces the magnitude of a TTS in humans, while an oxygen content of 60% has no effect (Patchett 1980). High oxygen content is used during high-altitude missions. The significance of higher-than-normal oxygen concentration in the prevention of noise-induced damage in these circumstances is not known. Oxygen concentrations of breathing gas were not measured in this study.

Furthermore, it may be difficult to observe a minor TTS when the study is run like the present one. The use of threshold increments of 5 dB in the measurements may render the observation of a small TTS difficult. Furthermore, it is not possible to conduct the measurements immediately upon returning from a flight. If a threshold shift recovers promptly, it will be hard to distinguish the change. The small number of subjects could also render the determination of a TTS difficult.

6.4 Permanent threshold shift (Study VI)

Noise exposure, hearing protection, and general health-related risks of pilots were exceptionally well documented in the present material. It is, therefore, safe to assume that various means of assessing the variables of the risk of hearing impairment were more reliable than is usually the case in many other occupational studies.

Even though noise levels at the entrance of the ear canal are rather high, approximately 90–100 dB(A), noise exposure among pilots remains relatively low because of the short duration of exposure. This kind of exposure in a working-aged population will probably not yield a good correlation between noise exposure and threshold levels, as age can mask other variables (Pyykkö et al. 1986). Ageing increases the amount of other risk factors (Pyykkö et al. 1986, Starck et al. 1999b, Toppila et al. 2001). When estimating with the ISO 1999 (1990) model, a small number of risk factors seems to reduce the hearing impairment risk estimation below the assumption, when the effect of noise is clearer. Therefore, at least the upper quartile (75th percentile) instead of the 50th percentile should be used in the ISO 1999 (1990) model when estimating the risk of hearing impairment among military pilots.
It has been shown that smoking together with other risk factors (Starck et al. 1999b) increases the risk of hearing impairment. In the group of military pilots, the number of other risk factors was small, and no effect of smoking on hearing could be found.

Generally, hearing in the left ear was worse than in the right ear. This difference may result in part from small firearm use. On the other hand, this kind of difference has also been demonstrated in other studies without the interference of shooting (Pirilä et al. 1991). The material in this study did not indicate any threshold deteriorations due to the firing of large-calibre arms; in fact, pilots are only seldom subjected to noise from these weapons during the early stages of their military training.

The study also reveals the importance of limiting the number of risk factors in the prevention of hearing impairment. Pilots have fewer risk factors, and their hearing threshold levels are better than in the group with more risk factors, such as high blood cholesterol, high blood pressure, smoking and moderate use of pain killers (Toppila et al. 2000).

A fighter pilot flies usually less than 150 hours yearly. During his entire career in the air force, a fighter pilot logs 1500 to 3000 hours of flight, which includes time on other aircraft. In comparison, the average annual working time in industry is approximately 1600 hours. So, according to the equal energy principle, the risk of NIHL in military pilots compared to that of industrial workers in Finland should be minimal.

It can be assumed that hearing impairment caused by aviation noise is possible at least among noise-sensitive fighter pilots (Pääkkönen & Kuronen 1996). Based on the exposure approximation, despite the small TTSs found the study V, the risk of a PTS among Finnish Air Force military pilots remains small.

In the future it might be worth including the NoiseScan as a part of the annual health examination procedure for the military pilots as a data collecting method.
7 Conclusions and recommendations

*Exposure.* The aviation noise exposure of the pilots was high enough at the entrance of the ear canal to be able to cause NIHL. However, the total exposure time for military pilots remains at a level of 1500 to 3000 hours. Compared to the working hours of industrial workers, about 1600 hours yearly, the total noise exposure according to the equal energy principle remains fairly low. The risk of NIHL, according to the exposure data, remains very small.

*Protection.* According to the results, the hearing protection of the pilots in modern aircraft used nowadays in the FiAF with present protection devices can be assessed to be safe to hearing. However, during the 1970s and earlier, noise protection has not been at the present level. At that time noise protection during firing was not at a high enough level, either.

Good protection for every aircraft type and environment should be measured when new equipment and aircraft are evaluated and taken into operational use.

For technical maintenance personnel who work on the platform running the missions, noise protection is especially important because noise exposures are longer than for pilots and peak exposure levels are sometimes high. Working conditions can also expose them to leakage of the protectors. Even though their protecting capability is fairly good, it recommended that better communication and protection systems should be evaluated.

*Temporary threshold shift.* A temporary threshold shift could be found after one flight. However, the changes were small and clinically insignificant. The findings support the conclusion that the risk of NIHL for pilots is fairly low. The experiences from EHF audiometry were interesting and support future examinations at the beginning of the career of military pilots and periodically, e.g., five years, after the first measurement. The proposed practice might give more information for individual risk evaluation after the long-term survey.

*Permanent threshold shift.* The NoiseScan model produced new data which was not available earlier. The NoiseScan model is based on the ISO 1999 model and designed for the risk factors of NIHL. The results showed that military pilots, with few risk factors for NIHL, had better hearing levels at 4 kHz than in the standard population, and the difference increases with age. The results are in harmony with the findings of Toppila,
et al. (2000). The results also imply that the equal energy principle and the use of A-weighting can be applied to aviation noise.

Because of centralised annual examinations of the pilots, it is recommendable to include the NoiseScan model as a part of the data collecting system in the FiAF. After a long-term survey it is possible to make further conclusions on the usefulness of the NoiseScan in the prediction of individual NIHL.

**Risk of sudden hearing loss after jet fighters’ low-level overflights.** According to the results, it is highly unlikely to suffer acute acoustic trauma as in the cases of two subjects who claimed a PTS after overflights by FiAF jets. However, the flight altitude must be exceptionally low (50 m or lower), if an afterburner is not used, as is usually the situation when low-altitude missions are flown. The individual sensitivity to NIHL is also one possible factor. Also, certain conditions that may amplify propagated noise waves are possible. They are, however, practically impossible to show in a test arrangement. Compensation to these two subjects was paid by the insurance company. It was concluded that the descriptions of the incidents and medical examinations supported logically and reliably enough the situation that both PTS was really caused by the noise of overflights.

**General.** Concerning the occupational health of the FiAF, it has been concluded in this research programme – reasonably reliably – that aviation noise is not a significant risk of NIHL for the pilots if well-fitting hearing protection in technically good condition is used. It seems that extra protectors under the headsets and helmets are not necessary in aircraft presently used in the FiAF. However, because of individual sensitivity, development of a hearing survey programme will be suggested using a NoiseScan-type data analysis programme when more data has been collected for future conclusions. The programme can be easily included in annual examinations.

The use of EHF audiometry might be considered for research purposes during initial screening and later at intervals of, for example, 5 years, even though its value for occupational health surveillance is as yet unknown.

Furthermore, it may be concluded that future research should be directed to the noise environment and working conditions. A main area in operational military aviation will be an emphasis on communication under demanding hearing conditions. The importance of situational awareness in aviation will be a major issue, of which communication will be a part.
8 Summary

Exposure. The averaged noise levels during the flight of a fighter pilot varied in the cockpit from 96 to 100 dB and near the ear canal from 88 to 95 dB. Radio noise increased background noise by 4–10 dB in the ear canal of the pilot. Based on gathered data and on averaged flight hours (typically 1500–3000 hours), it is very reasonable to conclude that the risk of hearing impairment for pilots is not significant. On the other hand, the risk of NIHL can be estimated to be real for maintenance technicians, who work longer periods close to running aircraft, where total noise exposure is considerably higher, about 800 hours per year.

The noise protection of pilots can be estimated to be at a safe level in the FiAF. However, the demands of better speech intelligibility in a noisy environment will be an important research area in the future. The properties of the communication systems of helmets and headsets should be evaluated and developed for maintenance technicians operating on the platform.

Overflight exposure. If the minimum altitude of overflight by Finnish fighters is more than 300 m, there should be no risk of hearing loss for persons on the ground below the flight path. However, two claims of acute hearing loss after an overflight by FiAF jets have been presented. The subjects presented audiometric results and reported to have developed hearing loss in the 1990s in Finland. The connection between the incident and the hearing loss has a high probability. However, the reasons for those two hearing losses remain somewhat unclear. It is possible that the aircraft were lower than reported. That is possible because the flying altitude can sometimes vary, even below the planned mission altitude. Also, the individual sensitivity of the subjects might explain the PTS.

Protection. When A-weighted noise attenuation values were compared for reasons of simplicity, the noise attenuation values were 31 dB for the Silenta Super earmuffs, 27 dB for the Ampliguard earmuffs, 25 dB for the Alpha helmet plus active noise cancellation, 22 dB for the Alpha helmet, 21 dB for the FFV 113B helmet, 16 dB for the ACS helmet (unadjusted) and 10 dB for the ZSH-5 helmet. The effect of sunglasses reduced noise attenuation by 4 dB and the cushion cloth by only 1–2 dB. Active noise cancellation improved noise attenuation by 3–19 dB within the frequency range of 0.063–0.25 kHz. Noise attenuation of more than 20 dB is needed, because modern fighters and helicopters often have noise levels higher than 100 dB(A) in the cockpit.
In the design of new aviation helmets, the good qualities of headsets and helmets should be combined in order to improve noise attenuation over today's performance.

Temporary threshold shift. Noise exposure at the ear entrance varied from the Saab 35 Draken’s 87 dB(L₁₆₁₂), the Hawk’s 87 dB(L₁₆₁₂), the F-18 Hornet’s 91 dB(L₁₆₁₂), the Redigo’s 91 dB(L₁₆₁₂), to the Mig 21 Bis’s 95 dB(L₁₆₁₂). The pre-exposure hearing thresholds of our subjects were good. A minor TTS was observed by means of both conventional and EHF audiometry in all aircraft types.

The risk of noise-induced damage is, in all probability, rather low at the studied exposure levels. However, routine annual measurement by conventional audiometry will be retained in the Finnish Air Force. In order to obtain more information from EHF audiometry for a future research program, EHF audiometry will be recommended every fifth year.

Permanent threshold shift. Hearing among Finnish military pilots turned out to be better than predicted by the ISO model 1999 (1990). The best model of the pilots’ hearing loss was obtained using the 80% fractile of the ISO 1999 (1990) model. This finding was related to the small number of risk factors in this population, and it corresponds to the predictions of the NoiseScan model for a small number of risk factors. When entering their career, military pilots are selected carefully. They are in good physical condition and they have normal hearing. During their career their health is carefully monitored when compared with the normal population. Since the risk factors of hearing impairment are fairly well charted, it can be stated that aviation noise and shooting noise constitute a small but existing risk of a shift in their hearing threshold. The NoiseScan model can be used to evaluate the individual NIHL risk of military pilots.
References


