THE HAZARDS OF INTENSE SOUND AND ULTRASOUND
ON THE EAR

(Thesis presented for the degree of M.D. in the
University of Edinburgh)

— by —

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The progress of mechanisation in our generation has increased noise levels to such an extent that severe mental and physical discomfort can be experienced by those subjected to "noise". In many instances intense noise is accepted as inevitable but its control notwithstanding should be a challenge to acoustical engineers. Exposure to excessive noise is considered as part of the price that modern man pays for a highly mechanised civilisation. Occupational deafness however is the most widely recognised type of injury resulting from extreme noise. Ill-effects of noise though not consciously recognised do exist and are a constant drain on nervous and physical energy. Since the trend in this mechanical age of ours, particularly under modern conditions, is for greater speeds and power, we must expect higher intensities and a wider range of frequencies both airborne and structure borne.

A better understanding of the functioning of the human ear has come about since the advent of radio and the development of various kinds of reproducing and recording equipment. The detrimental effects of intense noise however have not received the same degree of attention. In many noisy occupations the hazard of ultimate impairment of auditory acuity is taken for granted. There is even difference of opinion as to whether noise is annoying, disturbing or capable of producing deafness. As an industrial problem intense noise has not received the attention it merits. It is by-passed by managements who do not clearly realise the possibility of increased efficiency and production through curtailment of noise.

Several factors have been responsible for this failure to recognise the problem, the main ones being:

(a) Ambiguity both in the understanding of what constitutes loss of useful hearing and the way it should be measured.
(b) The relatively recent development and standardisation of satisfactory instruments for measuring hearing loss.

(c) The attitude on the part of many that the situation is better left alone since to investigate the problem of noise would merely emphasise and invite attention to a condition which has never been properly defined.

(d) A reluctance on the part of workers to complain of any symptoms for fear it will bring about loss of employment or adversely affect their tenure.

(e) The question of compensation for loss of hearing from exposure to industrial noise.

The word "deafness" for the purpose of this thesis is applied to all degrees of impairment of hearing from that of a slight deficit to the case of total deafness, and of either temporary or permanent duration.

We must accept without reservation that a potential problem exists and that deafness can and will result from high noise levels in industry and elsewhere. Interpretation is admittedly complicated by the multitude of causes of deafness as it occurs at random in the population. Surveys have shown that from five to seven per cent of the school population have measurable defects of hearing. Rodin studied 36,191 school children (9 - 16 years) and found that 9.5 per cent had losses of 9 or more sensation units in one or both ears. Crowe and others in a study of 672 boys (8 - 14 years) found that less than 47.3 per cent had normal hearing. Beasley surveyed 14,364 persons (8 - 76 years) and observed that only 38 per cent had normal hearing.

Several workers have carried out observations amongst the general population. Such conditions as respiratory infection, pressure changes and a large number of other factors apart from industrial
noise exposure may cause deafness.

We must also consider the normal deterioration in hearing with age, into which the additional variables of race and sex enter. It is possible to differentiate the cause of some of the cases of deafness, but very often this cannot be done with certainty. Some losses of hearing however have similar and relatively constant characteristics. There is no doubt that in certain occupations associated with continual exposure to loud noise, a deafness results which with long exposure is progressive and may be permanent (McCoy).

The worker's deafness (because of its innocuous origin in the little used high frequency range) neither stimulates executive interest nor the interest of the worker himself as does a temporary injury such as a broken arm, with which the relationship between cause and effect is more evident.

II DEFINITION OF NOISE

Noise may be defined as audible airborne vibrations which produce a subjective impression of unpleasantness and discomfort in people who listen to it or hear it. The degree of unpleasantness and discomfort depend on the sound pressure level, the frequency distribution of the complex sound field, the duration of the sound and the susceptibility of the individual to the feeling of discomfort. The nuisance value of noise is affected by the psychological outlook of the individual. Noise which may be sweet music to devotees of such sport as "dirt track racing" may constitute a definite annoyance to people residing in the neighbourhood who are not interested in the pastime.
It would perhaps be an advantage at this stage to define certain terms loosely applied to noise, which have crept into current use, viz. sonic, ultrasonic and supersonic. Sonic frequencies are those which are appreciated as sound by the human ear. They lie between 32 and 20,000 cycles per second. Frequencies above 20,000 cycles per second are known as ultrasonic for they do not act upon the ear in such a way as to produce the sensation of sound. The term "supersonic" is employed in reference to speeds greater than that of sound, approximately 1,125 feet per second in air.

Noise has been defined as "Sound without agreeable or musical quality" (Webster) or as the old gentleman said, "Noise is anything that I don't want to hear". (Dennis). Gilbert stated that "Noise is the rapid and irregular succession of different auditory sensations", whilst Dennis said "Noise is sound produced by the irregular and unperiodical vibrations of a body of air". Perhaps the most acceptable definition of noise is "unwanted sound".

III HISTORICAL REVIEW

The relationship between exposure to intense noise and loss of hearing has been known for at least one hundred years. Fosbrooke in 1830 called attention to the frequent occurrence of deafness among blacksmiths and raised the question of the role noise played in this deafness. He published an article in the Lancet entitled "Pathology and treatment of Deafness". Barr in 1896 established noise as being a cause of deafness in boiler makers. Later it was found that other workers suffered a more or less typical hearing loss. Factory machinists, locomotive engineers, riveters, weavers, and, with the advent of flying,
pilots and engine test bed workers showed evidence of acoustic trauma. Bunch in 1937 made an exhaustive and historical survey of occupational and traumatic deafness and Larsen in 1939 published an account of professional deafness in shipyard and machine factory labourers. Larsen found that hearing was deficient in about 50 per cent of the men examined. Weston and Adams in 1935 carried out an investigation on the performance of weavers under varying conditions of noise. They found that excessive noise handicaps the normal daily work of weavers. This effect is not a temporary one occurring only in the initial stage of exposure to noise, but has been shown to exist in individuals who have for years been accustomed to excessive noise, as a normal accompaniment of their work. It is doubtful whether complete immunity from the inimical effects of excessive noise can ever be acquired so long as normal hearing is retained and the development of partial deafness appears to be the only effective protection which the individual can acquire. It is probable that in the psychological sense tolerance to noise can be established in some measure. It may be possible to become acclimatized to noise so that consciousness of its subjective effects, such as irritation or annoyance, ceases or becomes less acute. Some of the effects however remain and are revealed only by objective measurements. Weston and Adams concluded as a result of their investigations that with a noise intensity of 96 decibels, the effect is to lower the rate of output of weavers by about 3 per cent of that obtainable when the noise intensity is reduced to a level of 81 decibels. In terms of personal efficiency this is equivalent to an increase of about $7\frac{1}{2}$ per cent with subdued noise. In a purely manual process a $7\frac{1}{2}$ per cent increase of personal efficiency would result in a $7\frac{1}{2}$ per cent increase in output. This would indicate that noise is an important factor determining individual efficiency.
In Bulletin No. 166 of the New York Department of Labour it is stated that of 1,040 workers in noisy industries tested for deafness, the highest percentage of hearing impairment for any age group was from the noisiest industries. Of 246 persons in this group found to be deaf, 155 cases were traceable to industrial causes.

In his work "Occupational Deafness" W. G. Thompson states that 45 per cent of locomotive crew men have impaired hearing. McCord gives 52 percent as the incidence of deafness among train dispatchers, and this occurs largely in the ear using the telephone. Recent studies on the effects of noise in military aircraft have shewn noise levels in multi-engined aircraft to be between 120 and 130 decibels. Even after an hour's flying with no protection to the ears a hearing loss of an appreciable degree will be noted. In his paper "Acoustic Trauma" Perlman states that many types of sound stimuli are known to be injurious to the ear and he lists among these the noises of pneumatically driven tools, Diesel engines and locomotive whistles.

Though occupational deafness is the recognised type of injury resulting from extreme noise, we must not lose sight of the less obvious, but none the less serious, nervous fatigue which it induces. Smith and Laird found in four healthy persons a decrease of 37 per cent in the number of stomach contractions from exposure to sound levels of 80 to 90 decibels. Experiments on decerebrated dogs have shown that auditory stimulation produced reflex responses in the entire sympathetic nervous system. Laird reported that the metabolic rate of four typists working at a maximum speed decreased from 74 per cent to 52 per cent over the rate when at rest, as a result of a 7 decibel drop in the noise level.
Gortstein and Kayser found that of 75 smiths and machinists 40 per cent were definitely hard of hearing and only 39 per cent had normal hearing.

IV PHYSICAL METHODS OF EVALUATING AND MEASURING SOUND AND ULTRASOUND

A brief account of the characteristics of sound and its measurement may help in understanding the problem of noise as it affects individuals. There is a great deal of confusion caused by lack of agreement on basic terminology, reference levels and methods of measurement.

Physical sound is produced by an alteration in pressure displacement or velocity of particles in an elastic medium such as air. The back and forth movement of the prongs of a vibrating tuning fork sets up alternate rarefactions and compressions in the surrounding air. These waves have definite physical characteristics such as amplitude, frequency, velocity of propagation and form and give rise to subjective sensations by their action on the ear and its associated nerve endings. If sound intensities are increased beyond certain values they are not only heard but also felt and their effect varying with the individual will be interpreted as discomfort, tickle or pain. Sound waves in air under standard atmospheric conditions and at 68°F travel at 1,125 feet per second. When we make acoustical measurements of sound we usually measure its pressure rather than its amplitude of vibration. Intensity is a measure of the energy which is associated with sounds and it depends on the amplitude or pressure. Energy which is associated with the motion of air particles, is proportional to the square of the amplitude of their movement, at a particular frequency or at any frequency, to the square of the pressure or of the particle velocity in the displaced air mass or
sound wave. Sound intensity may be defined as the rate of flow of sound energy through unit of area and is measured in watts per square centimetre.

The ear, while it is very sensitive to very small variations of pressure in the air, can also tolerate very large ones. For convenience we use the logarithmic scale to describe the very wide range of sound intensities to which the ear will respond. It so happens that the ear itself responds approximately logarithmically to sound. By this we mean that if two sounds of equal intensity are present at the same time, the resulting sound has twice the intensity but not twice the loudness. In other words, the sensation of loudness experienced is more nearly proportional to the logarithmic rather than the arithmetical sum of the combined intensities. The unit we use for measuring sound intensity is the "decibel" which, it must be appreciated, is a ratio of powers rather than an actual physical quantity. It expresses how much greater one sound intensity is than another. A reference level has been adopted from which all other intensities are expressed in terms of decibels above or below it. The one commonly used is an intensity of \(1 \times 10^{-16}\) watts per square centimetre which represents the minimum audible intensity at 1,000 cycles per second. This corresponds to a sound pressure of \(0.0002\) dynes per square centimetre and it represents the reference level adopted as the standard for all acoustical measurements (Figure 1).

When we consider noise in terms of the decibel scale we can see that if a source of sound has an intensity of 100 decibels (referred to the reference level) and a second source of noise of the same intensity is added to it, the resulting overall noise will be 103 decibels and not 200 decibels. The logarithmic characteristic of the response of the ear to sound thus safeguards it from the painful effect of noise (which usually
Graph showing the area of auditory sensitivity of human subjects. It shows the great variation in sensitivity for tones of different frequency. The range of greatest sensitivity falls between 500 and 7,000 c.p.s. and in the frequency range of greatest importance for the intelligibility of speech. The threshold of feeling is the level at which individuals exposed to these intensities experience discomfort or pain. (After Fletcher and Watson)
becomes apparent in the region of 120-130 decibels).

The mechanical vibrations entering the inner ear are converted into nerve impulses, and are in turn interpreted as the sensation of hearing. The basilar membrane in the cochlea contains nerve endings; it responds at its basal end to high frequencies and its apical end to low frequencies. Loudness is believed to be dependant on the total number of fibres activated. Our main concern in noise reduction is its loudness, or the subjective sensation of the strength of a noise. The sensation of the loudness is a complex phenomenon. It depends on the frequency and the intensity level of the sound. The ear responds in such a way that two tones of the same intensity but of different frequencies do not necessarily appear equally loud. Likewise if two equally loud tones of different frequencies are increased in intensity by equal amounts there is usually an unequal increase in the sensation of loudness. Thus, an 80 cycles per second sound with an intensity level of 60 decibels seems as loud as one of 6,000 c.p.s. at 40 decibels or one of 1,000 c.p.s. at 30 decibels.

The ear is much less sensitive at low intensity levels to low frequency tones than to those of 500 - 5,000 cycles per second. Above an intensity of 90 decibels the sensitivity of the ear is fairly constant over the entire frequency range.

The difficulty of hearing a given sound or understanding the spoken word in a "background of noise" is due to the masking effect of such noise. It becomes necessary to raise the intensity of such a sound or word to make it audible and this increase of the threshold intensity in decibels represents the degree to which it was masked by the ambient noise. In order to ascertain the component vibrations or frequencies
in a complex sound wave we use instruments known as wave analysers. Analysis may be made in as much detail as desired. For example by using a narrow band filter of say 5 cycles per second (Figure 2) the frequency range is covered in 5 cycle intervals.
It is however more practical and less time consuming to use filters of wider band width and for this purpose we have Octave Band Analysers. (Figure 3). These cover the frequency range 40 to 10,000 cycles per second in octave intervals.

S. T. & C. Octave Band Noise Analyser

Figure 3
The accompanying figures of narrow band and octave band analyses of aircraft noise is shown to illustrate these points. (Figures 4, 5 and 6).
Measurements taken on test bed: microphone 25 feet from end of jet pipe, alongside hole in exhaust tunnel.

Engine Speed: 10,250 R.P.M. Thrust: 5,000 lbs.

Figure 5
Figure 6
To measure the overall sound pressure level a General Radio type 759B sound level meter (Figure 7) can be used.

It must be appreciated that no sound level meter can simulate the response of the human ear, over the entire frequency and intensity ranges unless it is a complex and bulky piece of equipment. To meet these shortcomings, sound level meters are constructed with three response versus frequency characteristics.
(a) Flat network or one which simulates the ear's responses to high level sounds.

(b) 70 decibels network or one which simulates the ear's loudness response curve to a stimulus of 70 decibels.

(c) 40 decibels network or one which simulates the ear's loudness response curve to a stimulus of 40 decibels.

In order better to understand the relationship levels of noise of certain intensity, the following table (Table I) is reproduced from Ross McFarland's book.

<table>
<thead>
<tr>
<th>Conversation Level</th>
<th>Noise Level in Decibels</th>
<th>Air or land travel</th>
<th>Interior Building</th>
<th>Outdoor environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impossible</td>
<td>115-130</td>
<td>Pilot's compartment in modern combat aircraft</td>
<td>-</td>
<td>Riveter</td>
</tr>
<tr>
<td>Very difficult</td>
<td>80-95</td>
<td>Sports car</td>
<td>Loud indoor radio</td>
<td>Very heavy traffic</td>
</tr>
<tr>
<td>Raised voice</td>
<td>60-75</td>
<td>Railway sleeper</td>
<td>Noisy Restaurant. Dept. of large store</td>
<td>Brisk traffic.</td>
</tr>
<tr>
<td>Whisper</td>
<td>0-30</td>
<td>-</td>
<td>Quiet residence Studio for filming.</td>
<td>A quiet garden in a London square.</td>
</tr>
</tbody>
</table>

*TABLE I*
Sabine and Wilson measured the noise levels of various machines in decibels at a distance of 3 feet, and obtained the following values. (Table II).

<table>
<thead>
<tr>
<th>Noise level in decibels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch presses of various types</td>
</tr>
<tr>
<td>Bumping Hammer</td>
</tr>
<tr>
<td>Hydraulic Press</td>
</tr>
<tr>
<td>Automatic Riveter</td>
</tr>
<tr>
<td>Airplane Propeller Grinding</td>
</tr>
<tr>
<td>Wood planers</td>
</tr>
<tr>
<td>Wood saw</td>
</tr>
<tr>
<td>Riveting gun</td>
</tr>
</tbody>
</table>

**TABLE II**

The following table (Table III) expresses some of these noise levels in decibels in terms of amplification ratios:

<table>
<thead>
<tr>
<th>Noise level in Decibels</th>
<th>Physical Intensity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>1,000</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>100,000</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>1,000,000</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>10,000,000</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>100,000,000</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>1,000,000,000</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>10,000,000,000</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>100,000,000,000</td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>1,000,000,000,000</td>
<td></td>
</tr>
<tr>
<td>130</td>
<td>10,000,000,000,000</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE III**

<table>
<thead>
<tr>
<th>Threshold of hearing</th>
<th>Ordinary conversation</th>
<th>Threshold of pain</th>
</tr>
</thead>
</table>
The foregoing methods are applicable in evaluating frequencies in the sonic range. The problem becomes more involved when we try to measure and analyse frequencies in the ultrasonic field. Equipment is complicated and the design and calibration of a microphone in air for this purpose presents many difficulties.

Specialised receptors of the ear appreciate the sonic frequencies which extend from 32 - 20,000 cycles per second. Beyond this range we come into the realm of ultrasonics. Ultrasonic vibrations, usually known as Ultrasonics, refer to sound waves at frequencies above the upper limit of human hearing. They have a short wave length, form relatively sharp sound shadows, can be focussed to give intense local pressures and are attenuated more readily as they travel through air.

For the last two years we have been engaged in the Acoustics Laboratory of my department in developing equipment which will record not only the presence of ultrasonic radiation in air but also analyse the radiation in terms of frequency and intensity. In order to study any effects it is important to know the potential energy present. The accompanying figures (8 - 10) show in some detail the type of equipment used and figure 11 is an analysis of the sound emitted by a turbo-jet engine on the test bed obtained by using the equipment. This extends in the ultrasonic region up to 100,000 cycles per second.
Ultrasonic and Analyser Equipment

Figure 8

Modification R.A.F. Ultrasonic Analyser Equipment, embodying Dawe Ultrasonic Analyser

Figure 9
High Frequency Spectrometer

Figure 10
The term "acoustic trauma" has been given to the resultant effects, whether temporary or permanent following exposure to noise. There are certain factors which, because they influence the degree of hearing loss resulting from acoustic trauma, must be considered. These can be summarised as follows:

(a) Total time of exposure
(b) Length of exposure per period
(c) Loudness or intensity of the stimulus
(d) Character of the sound stimulus whether continuous or interrupted.
(e) Frequency of the noise. (By this is meant the frequency characteristics which go to make up the noise).
(f) The type of environment.
(g) Whether any protective devices have been used
(h) The age of the individual exposed. (Older persons probably are more susceptible and have less recuperative power).
(i) History of any previous aural disease.
(j) Constitutional factors such as differences in sensitivity.

Noise exceeding in intensity a level of 80 decibels is responsible for acoustic trauma. The impressionable ear may have permanent damage inflicted. Frequencies vital to the appreciation of speech may become so affected as to interfere with intelligibility.

Interrupted sounds are more traumatising than constant sounds. We can compare this to interrupted tactile stimuli which are more annoying than constant touch. Similarly, blinking lights are more disturbing than lights of constant intensity. A noise of low pitch is less displeasing than a high pitched tone. A nonabsorbent surface (e.g. a
steel plate) reflects as much as 80 - 90 per cent of the sound energy striking it. Whether the noise originates in the boiler maker's shop or is heard in the test bed of an aeroplane engine, or in the cabin of a noisy aircraft, the earliest manifestation of the insult inflicted on the aural mechanism is an abrupt dip or gap in the hearing range as determined by the audiometer near C5. (4096 cycles per second). It is important to emphasise that individuals with this loss give no indication that their auditory acuity is impaired. This is not uncommonly the case however in hearing loss which involves the clarity more than the apparent loudness of speech. Errors in hearing what is said are certain to occur at least occasionally in daily life, but they either pass unnoticed or are attributed by the listener to inefficiency on the part of the speaker. Dickson, Ewing and Littler demonstrated in 1938 the occurrence of this early loss in aviators and stated that the auditory defect was probably progressive in character if exposure to intense noise was continuous. The involvement to any marked degree of frequencies throughout the upper half of the speech range (i.e. above 1,000 cycles per second) would reduce the accuracy with which speech is heard to approximately 40 per cent. Dickson et al reproduced the dip or gap by one of them exposing his unprotected ears to very loud aeroplane noise during flights in multi-engined aircraft. Audiograms were taken immediately before and after the flights which varied in duration.

Noise and vibrations in piston-engined aircraft are derived principally from propellers, engine exhausts, moving parts of instrumental equipment, slip stream, and vibrating structures inside and outside the cabin. Of all these sources of sound the propeller tips and the motor explosions are responsible for most of the intense acoustic environment.
Analyses of this noise (Figures 12, 13 and 14) reveal that low and middle sonic frequencies predominate whereas in a jet-propelled aircraft (Figure 15) the principal feature in the corresponding spectrum are high sonic frequencies.
OCTAVE BAND ANALYSIS OF NOISE SPECTRUM 375 - 12500 C.P.

LINCOLN IN FLIGHT. NAVIGATORS POSITION.

Engine running conditions:
- 1900 r.p.m. + 7 lbs boost, Slow cruise. Modified Exhaust Stubs.
- 2300 r.p.m. + 4 lbs boost, Slow cruise. 
- 1300 r.p.m. + 7 lbs boost, Slow cruise. Further Modified Exhaust Stubs.
OCTAVE BAND ANALYSIS OF "LINCOLN" 240-1240 C.F.S.

ENGINE RUNNING CONDITIONS;

- 1800 r.p.m. + 7 lbs boost, Slow cruise, Old modified exhaust stubs.
- 2500 r.p.m. + 10 lbs boost, Slow cruise.
- 4500 r.p.m. + 7 lbs boost, Slow cruise, Further modified exhaust stubs.

PILOT'S HEAD POSITIONS:

LINED UP IN FLIGHT.

Frequency in C.F.S.
Measurements taken on test bed. Microphone along side engine and three feet from it.

Engine Speed, 3800 r.p.m.
Numerous reports from careful observers have appeared during and since the war with particular reference to the types of acoustic trauma. These can be classified broadly into:

(a) Explosive and
(b) Chronic noise deafness

In the former (a) trauma follows acute concussion of the inner ear which damages the cochlea and produces profound and permanent nerve deafness. Losses may occur at all the frequencies or more frequently the high ones specifically. Trauma may arise from any sudden and very loud noise which occurs close to the unprotected ear. The loss may be immediate and almost always permanent. (Figures 16 - 23 illustrate these points).

Figure 16

Audiogram of a man aged 33 who suffered deafness and tinnitus following the bursting of a shell. He was knocked unconscious. Experienced pain in both ears. No bleeding. Seen 12 months after the incident. Deafness and tinnitus persists. The tympanic membranes are normal.
Audiogram showing the effect of exposure to the radio beam. The intensity of the beam was 80 decibels. The duration about half an hour and the frequency of the beam was 1020 cycles per second. The graph shows the air conduction (---e--), findings in the exposed ear before and after exposure (---0---).

Figure 17

Audiogram of a member of gun crew knocked down by blast of detonator from 5 inch gun. Cotton wool plugs loosely worn. Tinnitus ++. No change in hearing after one year.

Figure 18
Audiogram of a man whose right ear was exposed to one single round of fire from a 90 mm. gun located at 10 feet to his right. He experienced pain in his right ear. Deaf in both ears immediately following exposure. Hearing returned in left ear after two months, but deafness persisted in right ear when examined eighteen months after. Tinnitus ++ has persisted.

**Figure 19**

Audiogram of a riveter showing acoustic trauma, confined to high tones. Rinne positive right and left. Weber not lateralised.

**Figure 20**
Audiogram of a riveter in an aeroplane factory - a typical graph of acoustic trauma. A year ago his audiogram was normal. His Rinne is positive in both ears, and Weber is not lateralised.

**Figure 21**

Audiogram of a man working on a Diesel engine of a patrol craft. Average daily exposure 8 hours for 26 days in the month. Has experienced difficulty in his hearing lately. Wears ear defenders only occasionally. The audiogram shows involvement of critical speech frequencies.

**Figure 22**
Audiogram of a man aged 27 who became deaf in right ear after firing a Colt pistol of .45 calibre in an indoor range. Tinnitus ++. Hearing loss persisted when last seen eighteen months after the incident.

**Figure 23**

In the latter (b) the deafness follows insults from long continued exposure to loud noise. Perlman has demonstrated that sounds of high frequency produce greater acoustic trauma than those of low frequency. It has also been shewn that the traumatising effect from interrupted sharp sounds is greater than that from a continuous sound of similar frequency, intensity and duration.

Weiss classified noises into two general types:

1. Sudden loud detonations, either single (as large calibre gunfire, bursting bombs, shells, explosion of mines, or depth charges) or repeated, as in the fire of smaller calibre weapons ranging from rifles to 200 mm guns.

2. Prolonged noise in connection with aircraft, tanks, or radio operations.
Having examined 33 cases of deafness due to acoustic trauma Weiss summarised his findings thus:—

Deafness unilateral 12 = 36.5%
" bilateral 21 = 63.7%

Tinnitus slight 15 = 44.7%
" persistent 16 = 47.1%

H. Davis, Morgan et al report that the ears of 15 young men (17 - 21 years) and four older men (29 - 46 years) were respectively exposed at intervals of several days to intense tones of frequencies 500, 1,000, 2,000 and 4,000 cycles at each of the intensities 110, 120 and 130 decibels for periods of one to sixty minutes. A noise of continuous frequency spectrum, somewhat resembling aeroplane noise, was also employed. After every exposure tests were made of the threshold of hearing and the ability to understand words through a microphone. Temporary impairment of hearing was regularly produced but there was no evidence of cumulative injurious effects. No significant raising of auditory threshold is produced for tones of frequency lower than the exposure tone. The greatest hearing loss occurs at a frequency about half an octave above the exposure tone. With longer exposures the hearing loss may be quite extensive for all tones above the exposure frequency.

Taking as a measure of hearing loss the average loss through the two octaves above the exposure tone we find that:

(1) 1,000 and 2,000 cycles per second are about equally effective in producing hearing loss.

(2) 4,000 cycles is much more effective and 500 cycles is much less effective than 1,000 or 2,000 cycles.
(3) Hearing loss develops most rapidly during the first minutes of exposure and then more and more slowly.

(4) More intense tones usually cause greater hearing losses but a one minute exposure to 2,000 cycles may be less effective at 135 decibels than at 125 or 130 decibels.

(5) Recovery of hearing usually begins rapidly and then progresses more and more slowly. It may require four to five days to recover from a 60 decibel hearing loss. Recovery tends to be slowest for frequencies at about 4,000 cycles regardless of the frequency of the original exposure tone. Some people are much more susceptible than others to the production of hearing loss, likewise the rate of recovery from a given degree of loss may vary.

Observations after personal exposure to jet engine sound intensity of approximately 145 decibels enabled us to determine the rate of recovery which followed such exposure. The maximum energy output occurred in the region of 2,000 cycles per second. Two exposures to the noises with ears unprotected were carried out (See Tables IV and V).

<table>
<thead>
<tr>
<th>Subject 'A'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of exposure 35 minutes. 30 feet from source and facing it. Audiogram taken 10 minutes after exposure.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Right Ear</th>
<th></th>
<th>Left Ear</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Difference</td>
<td>After</td>
<td>Before</td>
<td>Frequency</td>
</tr>
<tr>
<td>35</td>
<td>40</td>
<td>5</td>
<td>8192</td>
</tr>
<tr>
<td>70</td>
<td>70</td>
<td>0</td>
<td>4096</td>
</tr>
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<td>60</td>
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<td>0</td>
<td>2248</td>
</tr>
<tr>
<td>20</td>
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<td>1024</td>
</tr>
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<td>20</td>
<td>10</td>
<td>512</td>
</tr>
<tr>
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<td>15</td>
<td>256</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>15</td>
<td>128</td>
</tr>
</tbody>
</table>

Marked tinnitus with severe degree of hearing loss to conversation voice resulted. Complete recovery 36 hours after exposure.

**TABLE IV**
Subject 'B'

Time of exposure 30 minutes. 15 minutes with right ear towards source of sound and 15 minutes with the left ear. Distance 15 feet from source.

<table>
<thead>
<tr>
<th></th>
<th>Right Ear</th>
<th>Frequency</th>
<th>Left Ear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8 7 6 5 4 3 2 1</td>
<td>1 2 3 4 5 6 7 8</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>10 40 35 45 45 65 0</td>
<td>0 55 45 45 40 25 10 5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5 30 30 85 50 65 0</td>
<td>0 4096 0 65 50 60 50 40 15 0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>5 10 10 25 20 35 0</td>
<td>0 204.8 0 45 35 30 25 20 5 0</td>
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<tr>
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<td>5 1024 0 30 30 20 20 15 5 0</td>
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</tr>
<tr>
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<td></td>
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<tr>
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<td>10 256 10 20 10 0 15 15 5 5</td>
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<tr>
<td>5</td>
<td>0 5 15 10 10 15 10</td>
<td>128 15 20 10 5 15 15 10 5</td>
<td></td>
</tr>
</tbody>
</table>

Note:--
1 = Audiogram taken before exposure
2 = Audiogram taken 10 minutes after exposure
3 = Audiogram taken 1½ hours after exposure
4 = Audiogram taken 6 hours after exposure
5 = Audiogram taken 21½ hours after exposure
6 = Audiogram taken 26 hours after exposure
7 = Audiogram taken 70 hours after exposure
8 = Audiogram taken 146 hours after exposure

TABLE V

It will be seen that the maximum hearing loss is approximately an octave above the peak frequency of about 2,000 cycles per second.

The impairment of hearing produced by exposure to loud tones or noise is of nerve type. Though the threshold may be elevated 50 or 60 decibels there may be little or no loudness loss for sounds at 100 decibels loudness level. An audiogram alone is not an adequate measure of the impairment of auditory function. The impairment of understanding speech is more closely related to the overall loudness loss at the intensity level at which the speech is heard than to the threshold audiogram or to the loudness loss in any special portion of the speech frequency range (400 - 4,000 cycles). Prolonged exposure to noise of wide frequency spectrum causes severe articulation loss at a low (40 decibels) loudness
level but only moderate loss at a High level (100 decibels).

Senturia took one hundred aviation cadets who heard a whispered voice at 20 feet, who had not more than 10 hours flying and had not been exposed to airplane noise for 30 days. He examined them at three periods of 70 hours flying. Of the initial 100, he only finished with 40 for retest and found:

(i) A small number of the ears showed slightly increased V notching and high tone loss but not a single ear showed any severe or unusual change in the type or the grade of hearing and loss.

(ii) In no case was there a loss which interfered with hearing speech.

The author carried out an investigation to ascertain whether auditory deterioration sets in during training of flying personnel and at what stage it becomes apparent, i.e. after how many hours flying. Two courses of pupils were selected, a total of 134, and they were followed through all the stages of their training, i.e. from elementary flying up to and including the completion of their operational training. A complete Ear Nose and Throat examination was carried out at each stage beginning on posting from their initial training wing. Audiometric checks were made,

(i) Before starting elementary flying
(ii) Before starting Senior flying training
(iii) Before starting operational training
(iv) On completion of operational training

Readings under (i) (ii) and (iii) were carried out at the flying units concerned under the best conditions available and with the minimum of background noise. The final audiometric examination was carried out in a sound proof room; the conditions therefore were better than at previous tests. Two pupils out of 134 were found on the initial examination to be suffering from defective hearing and were taken off the course. The type
of aircraft used during training were single or twin engined.  

For various reasons unconnected with aural causes several trainees were eliminated during or shortly after completing the elementary stage of their flying; consequently final observations were made on 65 pupils who completed all stages of their flying training. Of these, 21 were trained on single engined and 44 on twin engined aircraft. Of the 21 single engined pupils, 6 were transferred to twin engined aircraft at their operational training unit. The findings were as follows:

(a) Out of the 21 single engined pilots, 13 showed some loss at the end of their operational training period, but amongst these 13 are 5 out of the 6 who were transferred to twin engined aircraft. 4 of these 5 pilots showed no loss prior to transfer to twin engined aircraft. Thus out of the 15 pilots who had flown nothing but single engined aircraft, 8 showed some degree of hearing loss at 8192 and/or 4096 c.p.s.

(b) Of the 44 pilots who flew twin engined aircraft after leaving their elementary flying school, a loss for the same frequencies was found in 41.

(c) Of the 21 single engined pilots, 4 showed an appreciable loss prior to going to their O.T.U. whereas of the 44 twin engined pilots 16 showed a loss at the same stage.

(d) Only 1 case showed measurable loss at the end of the elementary flying course (60 hours flying in a Tiger moth aircraft)

(e) The average loss at 8192 c.p.s. for single engined pilots was 9 decibels and at 4096 c.p.s. was 7.5 decibels. Exactly twice as many ears were affected at the lower than at the higher frequency. One side was not affected more than the other.
(f) The average loss in the twin engined pilots at 8192 c.p.s. was 13 decibels and at 4096 c.p.s. 11.7 decibels, the right side being affected 39 times and the left side 26 times.

(g) It was found that 18 of the twin engined pilots had done some flying during their operational training without helmets and these flying times varied from 4 - 5 hours. 2 of these pilots showed no loss, one having flown 45 hours and the other 30 hours in Whitleys without ever wearing a helmet. These comprise 2 out of the 3 who out of the 44 show no loss at the end of their operational training. The remaining 16 showed an average loss at each frequency as follows, 8192 c.p.s. 12.3 decibels and 4096 c.p.s. 12.6 decibels. This corresponds very closely with the average loss shown by all twin engined pilots.

(u) The highest recordable loss for a single engined aircraft pilot at the end of his operational training period at 8192 c.p.s. was 20 decibels and the lowest 5 decibels. The highest recordable loss for the twin engined pilots at 8192 c.p.s. was 25 decibels, the lowest 5 decibels. The highest for 4096 c.p.s. is 35 decibels and the lowest 4 decibels.

The most noticeable factor arising out of the inquiry is that pilots flying twin engined aircraft are more prone to show a loss of auditory acuity than single engined pilots (41 of 42 pilots flying twin engined aircraft from elementary training onwards and 5 of 6 who were transferred to twin engined machines at operational training). This confirms previous observations, also including those on oneself.

The onset of a measurable loss restricted to high tones becomes
apparent at an early stage. Whether this loss is permanent or recoverable if all flying is discontinued has not been ascertained. Probably at this stage it is recoverable. Any loss which becomes manifest seems to make its appearances when high powered aircraft are flown. Only one pilot showed any loss at the end of the elementary flying period when only Tiger moths were used. The earliest time at which any loss measurable by audiometry shows itself is after an average flying time of approximately 80 - 100 hours. The loss found at the high frequencies 4096 and 8192 c.p.s. is in agreement with previous observations made, viz. that the loss is confined at first to these frequencies in those who have been exposed to noise for a considerable period. Predisposing factors are neglect to wear the flying helmet continuously and properly, or discarding it altogether.

Macle remarks on certain characteristics of losses. He found that the points of maximum depression are distributed equally among three frequencies, 2896, 4096, and 5792 cycles per second. This was observed on a mean audiogram obtained by plotting at each frequency the means of the records of 45 men.

Chamberlain studied aural fatigue and recovery on boiler makers and his findings show the same pattern of loss.

Campbell and Hargreaves studied airmen and noted that the first inflexion of the normal curve appeared at 4,096 cycles, but with more severe loss the adjacent frequencies 2,896 and 5,792 were affected to an almost equal degree. These men were exposed to sustained high noise levels from aircraft engines with most of the fatiguing force lying under 1,000 cycles per second.

Bunch observed tractor operators and telephone operators and
found that they showed similar points of maximum inflection.

Grow and Armstrong in 1941 stated that an aviator who is repeatedly subjected to noise of 80 to 90 decibels of intensity or above will usually show some loss of hearing after a period of years. They stated that this level of noise is rarely exceeded in small or sound proofed aircraft, but is usually exceeded in high powered military multi-engined aircraft. According to these authors a study of military pilots showed that 24 per cent of the group suffered a significant loss of hearing while a similar group of commercial pilots showed a much lower incidence of hearing loss.

Simonton in a recent paper read at the annual meeting of the Aero Medical Association, August 29/1949 reviewed his findings on the hearing of air-line pilots. In his study of the audiograms of 47 pilots taken at intervals of 10 years for each pilot, he found that loss of hearing of 36 of the 47 pilots was 15 or more decibels, in one or more frequencies. The majority of these losses were recorded for frequencies at or above 4,096 cycles per second. Nine pilots had a loss of 15 or more decibels in the frequencies of normal speech, that is 512 to 2,000 cycles per second. Four pilots had a final threshold of hearing which was greater than 30 decibels for one or more of the frequencies of speech in one or both ears. Simonton voices the opinion that loss of hearing attributable to flight is not a serious problem.

If the early pessimism concerning the fate of a pilot's hearing has now been replaced by complacency one should appreciate that there is no real cause for this. Noise whatever its origin does damage hearing. Only efficient sound proofing in civil aircraft and the incessant insistence that service aircrew should protect their ears against noise are two factors which reduce the danger and may justify the complacency.
In most of these studies a wide range in the amount of permanent injury present and resulting is recorded. In occupational deafness the variations of effects may be influenced by such factors as orientation of the external auditory meatus, its shape or the presence of cerumen. The dips initially occurring are nevertheless the prototypes of the permanent defects to come. Campbell found among aviators that recovery from small degrees of fatigue may be complete after periods of rest but that constant repetition of the insult had a cumulative effect which finally caused permanent loss.

\[ \text{V (b) EFFECTS OF INTENSE SOUND ON VESTIBULAR FUNCTION} \]

Dickson and Watson studied service personnel working with turbo-jet aircraft and noted the occasional occurrence of symptoms of unsteadiness, dizziness and lack of concentration. These disturbances were noticed chiefly in the vicinity of the impeller close to the air intake at the fore end of the engines.

The appearance of such subjective sensations seemed to be produced infrequently and erratically. Injudicious press reports of possible harmful effects resulting from exposure to ultrasonic frequencies generated by jet-engines led to a number of purely psychological disturbances being experienced by jet personnel. At first sight therefore, the assumption that they were psychological in origin provided a reasonable, though not altogether satisfactory explanation.

Study of the literature on this subject has revealed no clear conclusions.

A transient vestibular irritation induced by standing in close
proximity to turbo-jet engines when run at certain speeds has been experienced by many observers, including the author. It seems unlikely that this phenomenon is due solely to the presence of ultrasonic waves as was at first suggested. It is well known that stimulation of the vestibule can be caused by sufficiently loud acoustic stimuli. Frequency analyses have shown that sounds within the normal range of audibility can be generated by jet engines at such sufficiently high intensities that an adequate stimulus to the labyrinth is provided even in normal individuals. Some reports, nevertheless, indicate that frequencies above the normal sound range can also produce similar effects. Ultrasonic spectra reveal that during the test bed running of jet engines, frequencies above the range of audible sound are of so low an intensity as to be thought incapable of causing deleterious results.

During flight, conditions are very different. As the speed of an aircraft increases so do the number and intensity of ultrasonic frequencies. This is because such frequencies are mainly aerodynamic in origin.

Symptoms of disturbance of equilibrium have been experienced mostly on the ground and only occasionally during flight. The explanation is that the pilot of a jet aircraft is protected in two ways from the noise of his engines, firstly by his cabin, and secondly by wearing a tightly fitting protective helmet. Ground personnel, on the other hand, frequently approach dangerously near jet engines without wearing any form of protection whatever.

The lines of inquiry have been as follows:

1. Members of the Royal Air Force and workers in aircraft factories, who have been exposed to jet engine noise
have been questioned about the occurrence of any of the symptoms mentioned.

(ii) Personal exposure to jet engine noise in order to experience subjective phenomena at first hand.

(iii) Sonic and ultrasonic frequency analyses over the range within which the phenomena were produced.

(iv) Subjection of a patient with a positive fistula sign to a noise intensity of 120 decibels.

Perusal of the literature and reports suggested that various symptoms may be produced in personnel working on jet engines. Dickson and Chadwick investigated the problem of these vestibular disturbances.

Employees working on jet engines were interviewed. By the courtesy of the De Havilland Engineering Enterprise the men concerned were questioned to discover what were their views on the "mythical supersonic sickness". It was hoped to analyse the experiences (if any) they themselves had undergone.

It was soon evident that no symptoms of the nature of those being investigated had been experienced during actual flight by any of those people questioned. Dizziness and unsteadiness occurred only during the running of engines on the test bed or during the running up of jet engines on the airfield. The symptoms were mild in degree and none of the workmen regarded them with any seriousness. Such a thing as "supersonic sickness" was regarded as a figment of the journalist's imagination.

Symptoms were experienced only at certain positions in relation to the air intake and only during the running of the engine at certain speeds; they were accentuated by rapid acceleration and deceleration of the engine.
In general, symptoms were experienced within an arc between $30^\circ$ to $45^\circ$ to the axis of the intake and two yards away from it.

Descriptions were varied and vague. Everyone had great difficulty in describing the reactions. Terms such as "a general feeling of unsteadiness", "a hearing black-out", and "a feeling as if mildly intoxicated" were used. Although dizziness was spoken of, there was no actual sensation of falling. Nor was there nausea at the time, though this apparently occurred sometimes following an exposure. Perhaps the most comprehensive description was that given by one of the engineers who said that he experienced "a momentary sensation of imbalance" accompanied by "lack of power to think".

In order to verify these statements personal observations were made on engine test beds and near jet planes on the airfield. The following effects were observed when standing near the air intake:

(i) Standing to one side of the impellor and wearing plasticine ear plugs and a protective flying helmet, no unpleasant symptoms were noted.

(ii) Protected as above, but standing in the optimum position previously described in relation to the air intake, (i.e. two yards away and within the arc $30^\circ$ to $45^\circ$) there was one limited range of engine speeds throughout which the noise intensity seemed to be maximal and unpleasant. It was within this range that an unprotected observer signalled that he was experiencing unsteadiness.

(iii) Standing near the intake, without aural protection, but not at the critical position no unsteadiness was noted. At the critical revolutions per minute, however, the noise intensity seemed more marked and unpleasant than at other levels.
Aural pain was not experienced at this level, but only when the engines were operating at much greater speeds.

Standing in the critical position, without aural protection, a most unpleasant and disturbing sensation of general instability and weakness was experienced at the critical speed. This feeling is exceedingly difficult to describe. Nausea, true dizziness and visual disturbances were not apparent. A peculiarly unpleasant reverberation seemed to be passing through the head. Symptoms were produced either on the test beds or on the airfield in all the observers. The intensity of the symptoms varied, nor were they manifested in all individuals at the same engine revolutions per minute; symptoms were elicited at slightly different speeds in different individuals. No nystagmus was observed in those actually feeling unsteady. One of the experimenters was convinced that the intensity of the symptoms was accentuated by rapid turning movements of the body and by swaying backwards and forwards. I had previously been told that men passing through this "danger zone" during their work on the engines had sometimes been seen to sway or stagger momentarily. Symptoms were immediately abolished by blocking the external auditory canals with the finger.

On the particular engines on which these investigations have been carried out, symptoms occurred within running speeds ranging from 5,000 to 7,000 revolutions per minute. Analyses of the sound and ultrasound waves detectable at these speeds have been taken.
The occurrence of momentary unsteadiness, imbalance and lack of concentration followed later by nausea in jet engine employees is described.

The possibility of the vestibular apparatus being stimulated by the intense noise generated has been considered, though objections to this idea can be raised in view of the fact that no nystagmus was observed. The absence of a sensation of rotation has suggested the possibility of the utricle being the area stimulated. As far as is known this does not produce nystagmus. Another explanation may be that it is the result of unseen bombardments of the centre by impulses from a large part of the VIIIth Nerve. The effects might result from a central overflow of auditory impulses to neighbouring nuclei.

We have no grounds at the moment to suppose that ultrasonic frequencies are mainly responsible for these symptoms. The effects are largely due to high intensities and not to high frequencies as such.

That intense noise can provoke vestibular reactions is well-known. Camis (1930) gave a very full review of the relevant literature. He quoted Richard (1916) who working on guinea-pigs showed that responses to acoustic stimulation could still be obtained when both cochlea were destroyed, but not when bilateral destruction of the vestibular apparatus was also effected. Earlier, Kalischer (1909) had found that dogs trained to react in different ways to different sounds still responded when the whole labyrinth on one side and the cochlea on the other side were ablated.

It has even suggested that the semi-circular canals play some part in the actual process of hearing (Autenrieth Filippo Lussana 1868, Funs and Masani, 1891 Hensen). Deetjen in 1899 discovered that the vibration from a Klein's whistle caused movement of the perilymph in the canals.
The classical experiments of Tullio (1929) demonstrated that sound can stimulate the cristae direct and his observations were confirmed by Huizinga (1934, 1936).

Clinically, a number of cases of vertigo, induced by noise have been recorded. This phenomenon has been termed "Tullio's syndrome".

Lindsay (1947) describes two cases of Menieres syndrome in which the lateral semi-circular canal was opened.

Post-operatively both patients complained of a "sensation of unsteadiness in the presence of loud noises". The Tullio reflex was not, however, elicited in any of his series of otosclerotics who had undergone labyrinthine fenestration.

Cawthorne (1949) noted that the Tullio phenomenon was sometimes produced when a two stage operation for labyrinthine vertigo was undertaken. It occurred occasionally following the first operation, at which fenestration was performed, provided the stapes was normally mobile. At a subsequent operation evulsion of the membranous labyrinth was followed by disappearance of the reaction.

These findings are in agreement with the experimental observations of Huizinga. He found that in pigeons the Tullio phenomenon could still be elicited after destruction of the cochlea, provided the conducting mechanism remained intact.

Benjamins (1938) describing a case of cholesteatoma exhibiting the Tullio reflex and the presence of a positive fistula symptom also stresses the fact that an intact middle ear apparatus is necessary for the production of a Tullio reaction. This reaction disappeared in his case, following a radical operation.

Moulougnet and Poncelet report the case of a man complaining of vertigo on hearing the whistle of a train and suggest that intense
noise can cause sudden contraction of the intra-tympanic muscles, resulting in a sudden jerking of the stapes which sets the perilymph of the semi-circular canals in motion, or alternatively that there is direct stimulation of the semi-circular canals by sound waves. 

J. Tondorf has produced vestibular reactions in patients without any semi-circular canal fistula by employing increasing and decreasing sounds. It is interesting to compare this result with the recent observations of Schmalix (1949) concerning the production of acoustic trauma. He found that during the testing of motor and aircraft engines, screeching sounds of a rising and falling character were apt to be more injurious than noises which remained steady. 

Gerlins and de Kleyn described a case in which vestibular irritation (dizziness and nystagmus) was elicited by acoustic stimulation.

Until the advent of the turbo-jet engine, little serious notice had been taken of similar symptoms occurring in close proximity to the noise arising from reciprocating engines.

In our interviews with personnel at present employed on the maintenance and running of jet engines, several men who had experienced attacks of unsteadiness remarked that this peculiar imbalance had taken place in the vicinity of noisy piston-engines also.

In connection with this observation a personal communication received from Lennart Gisselsson of Lund, Sweden, is of interest. A 21 years old air-pilot complained of attacks of giddiness when piloting certain types of aircraft. His description of the attacks suggested the occurrence of some vestibular reaction. The attacks came on when the engine was running at a particular number of revolutions per minute. Giddiness on landing was experienced if the propellers were adjusted in such a manner as to produce a certain tone of strong intensity. Symptoms of giddiness disappeared if the cabin window was opened. This diminished
the noise intensity within the cockpit. Clinical examination, audiometry caloric and tuning fork tests were all normal. No fistula sign was elicited.

The effect of pure tones of high intensity was then tried. A pure tone frequency of 300 cycles per second was said by the patient to be the same tone as that causing symptoms whilst flying. At an intensity of 100 decibels above threshold, this sound caused him to feel giddy and third degree nystagmus was noted. Symptoms occurred only on stimulation of the left ear and the test was repeated several times, always with the same result.

Two somewhat similar cases have recently been examined in the Royal Air Force. The first case presented with a left-sided facial paralysis following a blow on the mastoid process. Examination showed a normal tympanic membrane, normal vestibular reactions and normal hearing when tested by pure tone audiometry. No fracture could be detected in X-ray photographs of his skull and temporal region. Placing of the base of a C256 tuning fork on the mastoid process of the affected side, made him at once experience both giddiness and nausea.

The other case complained of occasional attacks of vertigo. Dizziness and nystagmus occurred when a C256 tuning fork was held close to the auditory meatus. This was the only abnormal clinical finding detected.

In a further third case examined, it was thought that it might be possible to induce the occurrence of Tullio-like reactions. This patient suffered from a long standing bilateral chronic suppurative otitis media. Cholesteatoma formation was present and brisk positive fistula symptoms could be produced by stimulation of either ear. Cochlear function was good. He was placed in a sound field of synthetic "white"
aero-engine noise of approximately 120 decibels intensity. No symptoms of either giddiness or nausea were complained of and no nystagmus was observed. In this case there had been gross destruction of the normal middle ear structures. The negative findings on exposure to an intense sound field are therefore in agreement with the observations of other investigators.

Huizinga and Benjamins previously referred to, found that the direct impingement of sound waves upon the membranous labyrinth was not the only requisite in the production of the Tullio reflex. An intact and normally functioning ossicular chain has also to be present.

A narrow band analysis of the noise spectrum (50 - 60,000 c.p.s.) from one of the latest turbo-jet engines was carried out at a distance of six feet in front of the air intake. These readings were obtained whilst the engine was run on the test bed at 5,000, 6,000 and 7,000 revolutions per minute, i.e. the range of speeds within which "reactions" had occurred. (See Figure 11, p. 21).

Peak intensities occurred at the following frequencies:

<table>
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<tr>
<th>Engine speed 5,000 r.p.m.</th>
<th>Engine speed 6,000 r.p.m.</th>
<th>Engine speed 7,000 r.p.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>At cycles per second</td>
<td>Intensity in decibels.</td>
<td>At cycles per second</td>
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<td>1,600</td>
<td>125</td>
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<tr>
<td></td>
<td></td>
<td>60,000</td>
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</table>

It will be observed that throughout this range, noise intensities of from 125 to 130 decibels are produced by frequencies between 1,600 c.p.s.
and 4,400 c.p.s. but that in the ultrasonic range (above 20,000 c.p.s.)
the intensities do not exceed 80 decibels.

It is interesting to compare these findings with those described
by Benjamins (1936, 1938). He mentioned a case in which dizziness developed
in the presence of sounds above 80 decibels in intensity and between 1,600
to 3,000 c.p.s. and states that these are within the resonance region of
the external auditory canal (2,500 - 3,000 c.p.s.). Littler has
demonstrated that the normal external auditory meatus possesses a
characteristic natural period. It may act as a resonator, frequencies
in the vicinity of 3,000 cycles per second being thereby intensified.

The impression gained from personal observations and reference
to reports published and unpublished is that the frequency of any airborne
vibrations which may be generated are relatively unimportant. The
production of the observed phenomena appears mainly to be a function of
intensity rather than of frequency.

In his survey of the biological and psychological effects of
ultrasonics Hallowell Davis (1948) stresses also the importance of what
he terms "sonic ultra-intensities". In a later publication (1949), he
and his co-workers, Parrack and Eldredge place emphasis on the intensity
scale being of more importance than the frequency scale, when considering
the hazards of sound and ultrasound. They also state that damage is due
to high intensity, not to high frequency.
VI (a) EFFECTS OF ULTRASOUND ON AUDITORY FUNCTION

There is no evidence at present that ultrasound has any effect on auditory function. Nor is there evidence that any other nerve endings in the body are capable of informing the individual of the presence of ultrasonic radiation. Equipment is becoming available in the Acoustics Laboratory of my department for producing ultrasonic frequencies at high intensities and further studies will be undertaken.

We have little or no knowledge of the effects of ultrasonic vibrations on the human body. There is no evidence that airborne ultrasonics can produce any specific direct effect on the brain or other parts of the nervous system. In the realm of physics most of the work has been done in liquids, but little is known of the range, propagation and transmission of ultrasonic vibrations in gases. Their biological effects seem to be related to the enormous alternating local pressures which are produced in the tissues and to the local heating effects arising from the absorption of energy in dampening the vibrations. Very small organisms may be disintegrated and red blood corpuscles destroyed. Milk too has been pasteurised by ultrasonic vibrations.

Ultrasound can be easily reflected by the human skin. In contrast to this good reflection of the human skin, a furred animal absorbs a greater proportion of sound energy. This energy is turned into heat which may be sufficient to kill a small animal like a rat or mouse.

Certain claims have been made by German investigators into the beneficial effects of ultrasonics for certain forms of cancer and neuritis. We do not know yet how much margin of safety there may be
between any beneficial effects on diseased tissue and injurious effects on surrounding normal tissue.

The jet engine and the approach of trans-sonic flight have by their emphasis on the possibilities of ill-effects from ultrasonic vibrations stimulated thought on the physiological effects of such vibrations. They may arise from two sources. First the engine turbine and compressor are likely origins of ultrasound, as is the gas in the jet itself. Secondly, the air through which the aircraft travels causes a great deal of aerodynamic noise, the peak frequency of which has risen as aircraft speeds have increased. With further increase of speed a larger ultrasonic fraction is likely to be present. As aircraft speeds increase the sound intensities will increase in level as well as in pitch.

It is interesting to note that a freely streamlined aircraft is quieter than an operational one with open gun ports etc.

VI (b) EFFECTS OF ULTRASOUND ON VESTIBULAR FUNCTION

We have no grounds for supposing that ultrasonic frequencies are responsible for any vestibular symptoms. My previous observations made on disturbance of equilibrium led me to believe that the effects are largely due to high intensities and not to high frequencies as such. Recently however Vyslonzil (1949) has demonstrated that in guinea-pigs exposure of the labyrinth to ultrasonic waves resulted in nystagmus to the side which was exposed. Depending on the dosage employed, reduced activity and even complete suppression of labyrinthine activity could be produced by the action of ultrasonic waves.

It has been shown experimentally that the enormous pressure
differences between the crest and trough of an ultrasonic vibration can produce the condition known as cavitation. Cavities and hollows are formed which tend to fill with submicroscopic bubbles arising from gases dissolved in surrounding liquids. It is believed that the formation of such bubbles in the tissues is mainly responsible for the damaging effect of ultrasonics.

Possibly ultrasonic frequencies of the intensity detected might cause the formation of such gas bubbles in the endolymph although such a supposition is purely conjectural.

Huizinga however found that by introducing bubbles into the semi-circular canal fistulae of his experimental animals the Tullio reaction remained positive, even though the fistula was then blocked by wax.

A fistula, however, occluded without the presence of an air bubble caused this reaction to disappear. On this hypothesis Benjamin suggested that the Tullio phenomenon appearing in his patient might be due to the presence of air bubble in the perilymph. He did not give any explanation however of the possible etiology.

VII PATHOLOGICAL CHANGES RESULTING FROM INTENSE SOUND

We have very little evidence of the pathological changes which occur in the human cochlea when exposed to noise or frequencies of high intensity. Animal experiments however have been carried out and the work of Lurie, Davis and Hawkins deserves careful study. They exposed guinea pigs to pure tones of various frequencies at intensities from 140 to 150 decibels. They found that the least detectable anatomical
damage to the organ of Corti was the disappearance of the mesothelial cells in a limited area from the scala tympani surface of the Basilar membrane. This was produced by a frequency of 1,000 cycles per second at 140 decibels for three minutes. Severe and extensive damage is produced by more intense tones and by longer exposures. The damage produced by intense tones are degenerative changes with rupture and dislocation of the organ of Corti from the basilar membrane. They further observed that a few days or weeks after exposure to intense tones the organ of Corti disappears when it has been severely damaged and the nerve fibres and the ganglion cells begin to degenerate. Mild degrees of damage are localised but a severe exposure say of 150 decibels for several minutes caused widespread damage. Furthermore the damage tends to locate nearer the helicotrema when caused by low tones and nearer the round window when caused by high tones. Once the organ of Corti has been damaged and degeneration of cells is present, there is no regeneration of these cells. The final result is complete absorption of the damaged cells, with an accompanying degeneration of the nerve fibres and ganglion cells leading from the site of the lesions.

It is possible to cause severe and extensive damage to the organ of Corti by loud tones without apparent injury to the ear drum or ossicles. During the last war I observed that when the Tympanic Membrane had been ruptured as a result of a high explosive blast, the auditory acuity showed less impairment than when the membrane was intact. Presumably the energy expended in rupturing the membrane was not transmitted to the inner ear with the same force. Witmack and Popoff showed destructive changes at the commencement of the basilar membrane in the organ of Corti with resultant changes in the
neighbouring ganglion cells after prolonged exposure to high noise levels.

As was pointed out previously, acoustic trauma is characterised by a curve which is defective for high tones. It reaches a peak of depression at 4,096 cycles per second (See Figure 18, p. 29). Various reasons have been offered as to the reason why this area is more susceptible or vulnerable to noise:

(i) The basal cell of the cochlea being anatomically more exposed receives the brunt of any impact.

(ii) Vascular bifurcation in this area associated with a narrowing of the cochlear duct.

(iii) The effect of the intra-aural muscles, stapedius and tensor tympani. Hallowell Davis has stated that "the net effect of the contraction of the intra-aural muscles can best be described as a shift of the frequency towards the high tone end of the scale. The acoustic reflex apparently serves to protect the inner ear from damage from excessive amplitude of vibrations which might be caused by intense tones of low pitch".

(iv) The hair cells of Corti's organ in the basal turn of the cochlea are more vulnerable because they receive the greatest trauma.

Several observers have recorded the effects of exposure to noise and the rate of recovery. They invariably agree that constant repetition of the insult without adequate periods of rest has a cumulative effect resulting in permanent loss of hearing.

More recently (1949) Alexander and Githler have reported their observations on the effects of jet engine noise on the cochlear response.
of the guinea pig. They measured the cochlear potential at various intervals for four groups of guinea pigs after a 15 minute exposure to jet engine noise. A control (non-exposed) group was also tested. It was found that:

(i) Exposure to jet engine noise results in auditory impairment throughout the frequency range.

(ii) Partial recovery occurs progressively up to three weeks following exposure.

(iii) After injury, the cochlear potentials are further impaired on the presentation of even moderately intense sounds. The exposed ear has been rendered usually susceptible to further injury.

(iv) There is preliminary evidence that indicates the possibility that further degeneration occurs between three and six weeks after jet stimulation.

(v) Protected ears show no immediate effects in auditory acuity. These results are plainly in support of the use of protective devices by all persons concerned while an engine is operating. It is also interesting to find some support for an impression I have formed as a result of observations into the problem for many years, viz. that it appears the auditory damage once produced lowers the threshold of susceptibility to further damage. This may help to explain the puzzling nature of progressive auditory impairment we often find clinically.

Davis, Parrack and Eldridge in a recent paper report what they believe to be the first case of rupture of the human ear drum under experimental conditions by exposure to a sustained sound of measured intensity. The frequency was 6,500 cycles per second, the exposure lasted five
minutes and the intensity varied from 156 to 164 decibels depending on the position of the subject's head in the sound field. When the subject first placed his head in the sound field the pain was so intense that he was forced to withdraw his head for a few moments. He nevertheless kept his head in the field at the limit of the pain he could tolerate. He describes it as "not the ordinary sharp pain from sounds above 145 decibels but a new kind that included dull as well as sharp pain". At the end of the exposure there was blood in his external auditory meatus and otological examination showed a small rupture near the centre of the drum. The hearing in this ear was depressed above 1,000 cycles per second and was unmeasurable above 8,000 cycles per second. The drum healed well and normal hearing for most frequencies returned within a few days, but the loss for high tones above 9,000 cycles per second remained.

VIII PATHWAYS OF VIBRATION TO THE EAR

The basilar membrane of the cochlea may be put into oscillation by either vibrations transmitted to it via the Tympanic membrane, the ossicular chain and the endolymph of the scala vestibule or by vibration transmitted via the surrounding petrous temporal bone. It is not quite clear whether the method of production of oscillation of the membrane in the second method is by a translatory movement of the skull against the inertia of the ossicular chain (Tumarkin 1946), or by the transmission of compression and rarefaction waves through the skull tissues to the labyrinthine fluids. The frequency response characteristics of these pathways is not known nor their efficiency in transmitting single pulses of high energy content. The amount of damage resulting in the
cochlea from airborne and structure borne vibrations of equal energy content is not known, although Popoff reports that when two groups of rats were exposed to the noise of machinery (one group in a cage suspended by damping structure, the other placed on the bed of the machine), gross damage was done to the cochlea of those rats in the cage subject to structure borne vibrations and no damage was seen in the cochlea of the other group.

The body possesses two types of receptors for vibration appreciation, the vibration receptors of the skin and deeper tissues, and the cochlea. Both these receptors must have their sensitive element distorted by more than a certain amount and in a particular way before they give rise to such a massive discharge of nerve impulse to the central nervous system that the sensation produced is either painful or so intense that it preoccupies the whole of conscious thought.

The vibration receptors are susceptible over the range of 0 - 1,000 cycles per second approximately, and the cochlea, as already stated, over the range 20 - 20,000 cycles per second. Either will respond to distorting mechanical forces whatever their method of access, provided they are of sufficient intensity. Mechanical effects of vibration in body tissues are not clearly defined. Few structures in the body appear to have a resonant frequency, the more notable exception being the eyeball, which resonates at about 40 cycles per second and 80 cycles per second. It is possible that some structures in the central nervous system might resonate and that physiological disturbances may arise from this. The otoliths in the saccule and utricle for example might resonate and produce abnormal Labyrinthine sensations.
Coleman investigated the effects of vibrations on the human body. He found that the central nervous system reacted to them, and that the functioning of the patellar reflex was impaired. When individuals sitting on a specially constructed vibration-plate were subjected to vertical oscillations the patellar reflex could no longer be produced if a certain frequency and amplitude were exceeded. Long application of a weak vibration caused a slowly growing deterioration in the patellar reflex. Loeckle carried out a series of experiments to verify these findings. He used frequencies between 20 and 1,000 cycles per second and the maximum amplitude of the vibration table used was about 2 mm. at a frequency of 35 cycles per second. He applied mechanical vibrations to the whole body and to individual points. The resulting disappearance of the patellar reflex observed originally by Coleman was due to the effect of vibrations on the autonomic nervous system. The extent to which reflex activity is reduced and the period of time over which it occurs depend on the frequency, amplitude and length of time of the application of the vibrations. This is important when we are considering protective means against structure borne vibrations. Various parts of the body in contact with structures continuous with vibrating parts will have these vibrations transmitted to them. Transmitted vibrations will be influenced by the transmission factor of the tissues and the resonant structure within the body.

Russel Davis carried out an investigation on the effect of noise on the nervous system. He was particularly interested in fatigue and the human factor on the incidence of flying accidents. His experiments showed that noise did influence the performance, not as regards accuracy but in affecting the movements by which the accuracy was attained. The influence was not uniform; individuals being
affected differently. He concluded that the experiments confirmed
the presence of individual differences in the effects of noise on
efficiency in skilled jobs, but the importance of the effects remain
disputable.

IX  SAFEGUARDS AGAINST THE EFFECTS OF INTENSE SOUND

The obvious and direct safeguard is to reduce the noise level
in the working environment. We do know that levels of 100 decibels and
above will produce fatigue and deafness and that levels of 80 to 90
decibels are annoying. We have evidence that continued exposure to
levels of the order of 80 to 90 decibels for long periods of time may
lead to the acceleration of the normal deterioration in bearing which
occurs with age. It is often possible for an acoustically treated area
to be more comfortable than an untreated one having actually a lower
noise level. Reverberation is the prolongation of sound by repeated
reflections from highly reflecting walls and ceiling surfaces. In a
reverberant space the worker has the sensation of working at a noisy
machine in a noisy environment. But when the reflecting surfaces are
replaced by absorbing surfaces the environmental factor is reduced, thus
reducing the annoyance, even though the measured noise level is not
markedly decreased. Consideration must be given to the spreading effect
of sound. In an open space the intensity of sound from a given source
falls off rapidly as the distance increases. In a reverberant room
the sound intensity from a single source is almost independent of the
distance from the source and the sound spreads with little diminution.
With distance the absorbent treatment greatly reduces the spreading
effect and there is a feeling of relatively quiet surroundings.

The planning and lay-out to reduce factory noise should receive more attention. Isolation of heavy machines by means of effective shock mounting will reduce building vibrations which are transmitted throughout steel and concrete structures. The design of aeroplane test benches has shown what can be done in protecting workers from the effects of intense noise (Figure 24). Observation cabins properly insulated, house the necessary instruments, gauges and equipment. There the worker is exposed to a noise level of probably 80 to 90 decibels instead of 130 decibels on the actual engine bed.

When we consider dwelling places, especially those with thin cheaply built walls and floors which are but slight barriers to the passage of sound we realise that little attention has been directed to the problem. Even in modern flats the transmission of sound between adjacent apartments and between floors is frequently a cause for serious complaint. Insulation can be obtained, but it is expensive and it appears that low priced dwellings will never reap the benefit of such a procedure. Cheaper means of insulation should however be within the realm of possibility. Perhaps when we become fully alive to the fact that quiet living conditions are essential to the health and efficiency of the individual the question of noise will receive the attention it deserves in the planning of homes.

In addition to modifying the working environment and controlling noise at the source certain other measures should be taken which mainly concern the individual.
(Photograph by courtesy of De Havilland Engine Co.)

Figure 24.
(i) It is essential to carry out a survey of the level of sound present and if possible an analysis of its component frequencies.

(ii) All personnel exposed to an intensity of noise above 90 decibels should be examined audiometrically before engagement and thereafter at stated intervals. It is important however that the testing conditions and the equipment should both be standardised.

**Pure Tone Audiometer**

*Figure 25*
Procedure for testing R.A.F. candidates by Pure Tone Audiometry

(Operator sits on the left, while patient sits in sound proof booth)

Figure 26

R.A.F. Gramophone Audiometer at present in use

Figure 27
Prototype of new R.A.F. Gramophone Audiometer

Figure 28
(iii) If we are to be faced with claims for compensation for loss of hearing we require, as a minimum, data on the capacities for hearing of the individual prior to employment and his auditory progress whilst employed.

(iv) Repeated surveys of the worst exposed groups is indicated accompanied by the study of the magnitude and spectrum of the noise at various places in the occupation.

(v) We must institute systematic studies of sound levels in noisy industries for the increment of injury contributed by the occupation can only be evaluated in large groups of men in relation to measured noise levels. We have standardised instruments available for the purpose and somebody must make a start.

(vi) Where control of noise is not practicable, protection of personnel by efficient ear protection, such as ear wardens, or helmets is essential. (Figure 29). A person's judgement as to effects of exposure to noise or the necessity for protection are not always reliable.

(vii) Cotton wool reduces noise by 10 - 15 decibels; plugs by 20 - 30 decibels, but workers will not always wear them. The problem has been to devise ear protectors which not only eliminate the hazards of intense noise, but are comfortable enough to be acceptable to the worker so that he will voluntarily make use of them for long and repeated periods.

(Jack Weiss comments that objection to the use of plugs by gunners on the basis of inability to hear commands and signals is not valid because the loud spoken voice actually
Various types of Ear Wardens made of rubber or Neoprene

Figure 29
is heard better in a noisy environment when an ear warden is in place than when the ears are unguarded. The plug eliminates excessive extraneous noise).

(viii) Personnel working in noisy surroundings should be educated on the significance of protection against intense noise.

(ix) Rotation of personnel which would allow for recovery by rest. This may require four to six days. Unless however audiometry is practiced in certain occupations and there is opportunity for rotation which will necessitate men being away from high level noise for long periods the procedure is impracticable.

(x) It should be realised that there is a great range of magnitude in susceptibility. This suggests the desirability of screening new employees for susceptibility. No reports are available so far on this point, but it should be tested nevertheless. We have seen gunnery instructors and aviators with years of exposure who have never used ear protection and who have practically normal hearing.

Finally if preventive action against the noise hazard in industry is to be initiated and success in its application be expected certain fundamentals must be observed. The Sound Level Meter used should be calibrated immediately before the survey and when used should either be rested on a quiet surface or held in the hands. Measurements should as far as possible be taken at the ears of the workers subjected to noise and such record or chart should be kept on the basis of individual job noise levels.
McCoy suggests that the interpretation of the noise hazard survey should be according to the following factors:

(1) The sound intensity
(2) The total time and periods of exposure
(3) The type of ear defender and the constancy of its use
(4) A distinction as to type of noise whether continuous or interrupted.
(5) The immediate environment from the acoustical standpoint including the method of operation.
(6) The frequency of the noise.

**SUMMARY**

1. Noise can impair hearing by its intensity as well as by its duration. A single loud sound or explosion if occurring suddenly and unexpectedly is injurious.

2. The hearing loss is at first a reversible process but prolonged and sustained exposure to noise leads to irreversible changes. What at first appears to be a manifestation of fatigue may ultimately result in pathological changes.

3. Noise injures the most sensitive and vital parts of the organ of hearing.

4. The resulting deafness in certain noisy occupations constitutes what one might term an occupational hazard.
5. Not every human ear is injured by loud continual noise to the same extent. The healthier the organ of hearing, the less harmful is likely to be the effects of noise.

6. If hearing becomes impaired and it invariably is manifest at first in the high tones, the individual cannot hear whistles or tones of a high pitch. Prolongation of exposure to the effects of noise will result in the degenerative process of other cells of the cochlea and other frequencies will be impaired.

7. Impairment of hearing caused by noise is gradual in development and hardly noticed by the individual. Only examination by an otologist with reliable equipment at his disposal will reveal the initial loss.

8. An individual suffering from any ear disease or hearing impairment should be seen by an otologist if engaged in a noisy occupation. If engaged, frequent checks should be carried out.

9. If a worker finds that a noisy occupation impairs his hearing or affects his general well being, he should choose different work.

10. Every endeavour should be made to limit noise. It includes the proper distribution of machinery and suitable contrivances for the suppression or reduction of noise such as sound proofing.

11. Ear wardens should be worn in noisy occupations. Plugging the ears with cotton wool alone is not sufficient. A close fitting comfortable ear warden with an attenuation of 30 decibels should be used.
12. A partial hearing loss greater than would be expected on the basis of age alone seems to be statistically evident among workers in very noisy industries, including certain branches of military service. It is possible that many cases of definite hearing loss may be due to a single exposure to a louder than usual sound and not to a cumulative effect of more moderate exposures.

13. Present evidence does not indicate that air borne ultrasonic vibrations constitute a practical hazard to hearing or produce any specific effects on the nervous system or sense organs.

14. Sound above 120 decibels stimulates the sense of touch and may cause temporary and possibly permanent damage to hearing. Levels above this are harmful to the ear and exposure without special protection should be avoided.

15. Intense sound may give rise to a disturbance of equilibrium. This is regarded as a manifestation of sound intensity rather than one of frequency.

16. Special equipment, properly calibrated and maintained is necessary for the measurement of noise intensities, analysis of noise, and evaluation of hearing losses.

This Thesis is based on personal work and research carried out by the author since his appointment as Consultant in Otorhinolaryngology to the Royal Air Force. Some of the observations contained in this thesis are based on several papers and reports which have been published from time to time.
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