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THE EFFECTS OF AEROPLANE NOISE ON THE AUDITORY ACUITY OF AVIATORS: SOME PRELIMINARY REMARKS

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1. Introduction

A PARTIAL survey of the literature has disclosed no audiometric studies in the English language which demonstrate the effects of aeroplane noise on hearing. It is well known, however, that it can affect hearing adversely. Bunch in 1937 made an exhaustive and historical survey of occupational and traumatic deafness, which included some notes on deafness in aviators.

Bauer in 1926 stated that the constant noise of high powered motors causes diminution in hearing. The pilot who wears no protective device will invariably become markedly deaf. At first this deafness gradually wears off after a few hours, but constant flying without protection leads to permanent impairment of hearing.

Numerous experiments have shown that prolonged stimulation of the ear by very intense sound causes cochlear degeneration, resulting in deafness. Kawata subjected guinea pigs to noise for a month. The histological examination of the organ of hearing showed complete degeneration of the organ of Corti at the point of transition from the basal turn to the second coil of the cochlea. The chief partial tone used was f4.

Fowler in 1929 remarked that mid-high frequencies were particularly sensitive to various results especially acoustic trauma and toxic neuritis because they regularly fail to escape in these conditions. It would appear that there is an element of trauma that is diagnosable by the presence of marked deafness areas (dips) and not otherwise ascertainable.

More recently it has been found that the level determined by physicists as the limit of loudness which is tolerable to normal human listeners approximates to the physiological overloading point found in animal experiments. The noise produced by certain types of multi-engined aircraft has been measured and found to reach loudness levels which are indicated as injurious to human hearing. The loudness levels measured at the National Physical Laboratory and by us at the Experimental Establishment at Farnborough have shown intensities from 110-135 phons (B.S.). These levels vary with the type of aircraft and with the position of the occupants. With further increase in horsepower in later types of aeroplanes the occurrence of noise at considerably higher levels is predicted. These levels of loudness exceed those of noise in boilermakers' shops in which the incidence of chronic high tone deafness amongst employees has been found to be high.

2. Diagnosis of Aviators' Deafness

During the past few months audiometric tests have been carried out by one of us at the Central Medical Establishment, Royal Air Force, on airmen and pilots who have a varying number of flying hours to their credit.

Data have been collected with regard to the occurrence of high tone deafness amongst them, especially after regular flying, even after a few hundred hours, without helmets in enclosed cockpits. It also occurs amongst personnel engaged in testing and tuning multi-engined aircraft. There is a persistent loss of hearing for high tones which is evidenced at first by an abrupt dip or gap in the hearing range as determined by the audiometer

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near C5 (4096 Hertz). The following audiograms are typical of a number which have been obtained.

In these, Air conduction is shown by a continuous line, thus

×———× and ○———○

Bone conduction by a broken line, thus

△- - - -△ and □- - - -□

The discovery of these data has raised a number of serious considerations and calls for close study in the light of all our existing knowledge about occupational or traumatic deafness and the protection of hearing against excessive stimulation.

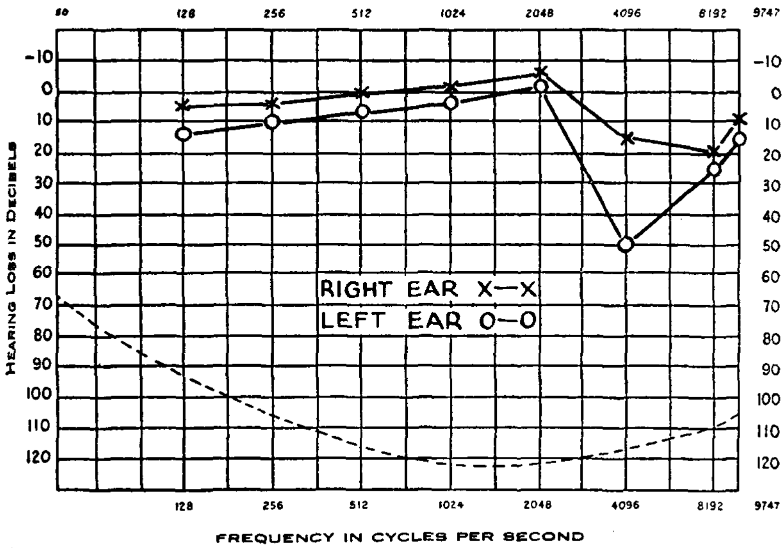
It should be emphasized that these patients gave no history of any previous ear trouble. In every instance a complete aural examination was carried out. The results of tests of hearing for speech confirmed the audiometric measurements. Mistakes in hearing the spoken word often occurred when accurate interpretation depended upon ability to recognize consonants whose essential characteristics are highness in frequency and weakness in intensity. Such mistakes are likely to be more numerous when the patients have to listen to speech in a noise, which masks the important high-pitched characteristic of consonants, or through a telephone which reproduces them with less than normal amplitude.

The patients themselves were not always aware that their auditory acuity was impaired. This is not uncommonly the case, however, in deafness which involves the clarity more than the apparent loudness of speech, and which is unaccompanied by pain or any other symptom usually associated with illness. 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 patient to inefficiency on the part of the speaker.

It is probable, however, that this form of auditory defect is progressive in character so long as the patient continues in his occupation of flying in, or tuning, very noisy aircraft. If this is so and if acuity to sound throughout the upper half of the speech range (i.e. above 1000 Hertz), is seriously involved, the accuracy with which speech is heard will be very severely reduced indeed—to approximately 40 per cent. of normal. Aviators' deafness must therefore be considered as potentially threatening a serious and life-long disability.

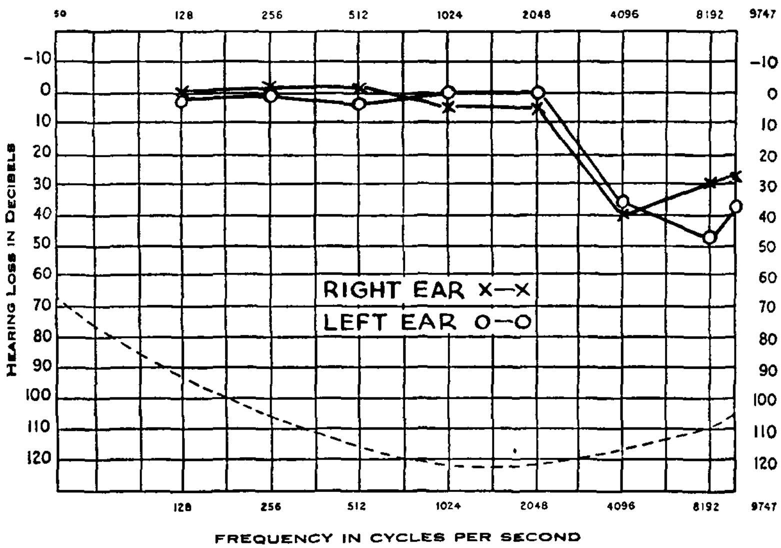
Audiograms showing loss of high tones in personnel exposed to continuous aeroplane engine noise.

Audiogram of W.H., age 23, date 1.6.38.



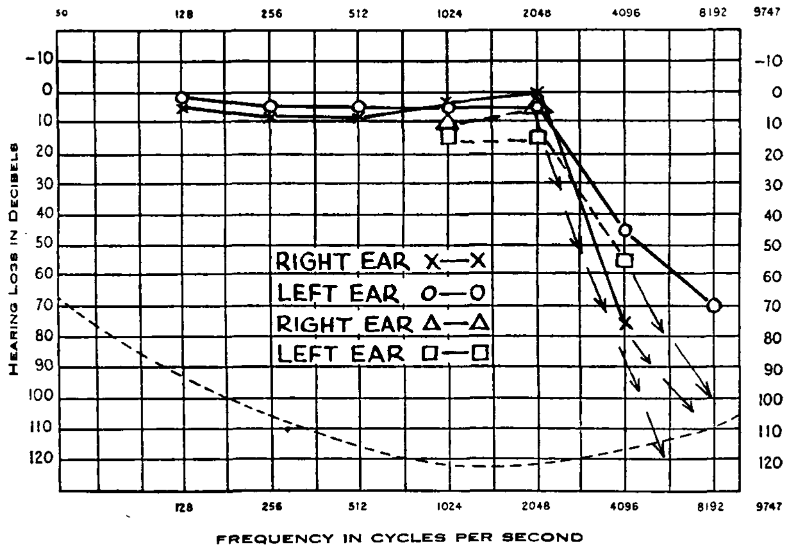
No previous history of ear trouble. Total flying 100 hours in twin-engined aircraft. No helmet worn. Tinnitus and deafness after landing lasting over one hour. Audiogram shows drop at 4096 Hertz with normal responses at 8192.

Audiogram of G.R.J., age 23, date 30.6.39.



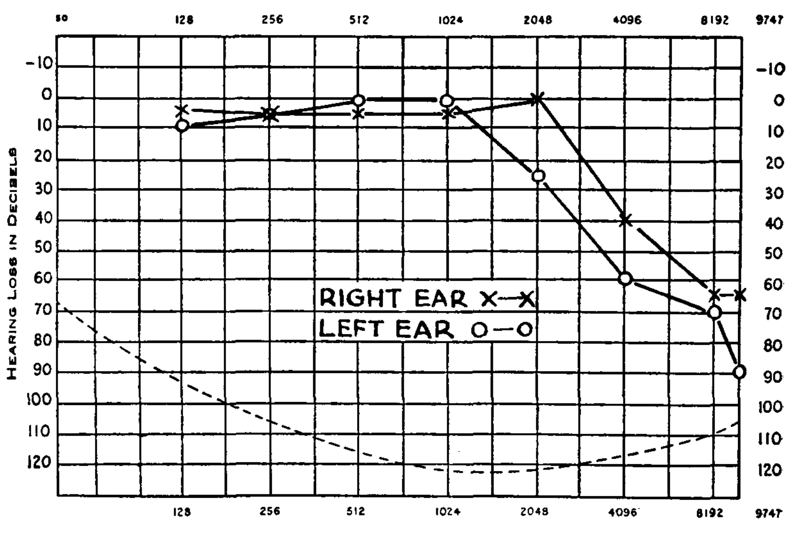
No history of ear trouble and no cause to account for high tone loss. Has flown twin-engined aircraft for last six months, 150 hours without helmet. Hearing "woolly" on landing. Engine h.p. 350 each. Two blade propeller.

Audiogram of L.C.D.B., age 24 years three months, date 27.2.38.



No history of ear trouble at any time. Eustachian tubes patent. Total flying 100 hours in twin-engined aircraft, but for last five years has been "running up" engines. Last two years with twin-engined squadron. Has never protected ears. Rinne +VE. B.C. diminished.

Audiogram of F.E.M.H., age 22 years 6 months, date 30.6.38.



Total flying about 200 hours all in flying boats and never wears a helmet. Sits amidships about 16 feet below engines. No history of ear trouble at any time and no other cause to account for high tone loss. B.C. shortened. Rinne +Ve. Hears C.V. 20 ft., just.

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In order further to study the immediate effects of very loud aeroplane noise on auditory acuity, audiograms of a pilot and of himself were made by one of the writers before and after flight in a twin-engined bomber. Both remained in the air for an hour without any attempt to protect the ears. The engine R.P.M. were from 1,800 to 2,200 and the noise level was approximately 119 phons, much below the maximum level reached in modern aircraft.

On landing audiograms were taken within ten minutes. The following points were noted :

(1) The ear nearer the engine was the deafer of the two.

(2) Tinnitus was present in this ear, lasting in the writer's case nearly three hours, and corresponding in pitch to about 4000 Hertz.

(3) Audiograms in both cases showed a characteristic dip at 4096 and 8192 Hertz with no appreciable loss for other frequencies, and more evident in the ear nearer the engine.

(4) *Pari passu* there is a loss by bone conduction corresponding to the loss of frequencies by air conduction.

(5) Subjective recovery of hearing took place within an hour.

Comparison of the two audiograms given above, which shows the extent of temporary deafness measured in two subjects with otherwise normal hearing, immediately after flight, with the three sample audiograms of chronic deafness found amongst Royal Air Force personnel, shows a similarity in character. In both sets of audiograms deafness is bilateral and is confined to frequencies above C^3 (1024 Hertz).

The temporary deafness measured in our experiment was less severe than in some of the chronic cases as will be seen from inspection of No. 1 and 2 of the audiograms already quoted.

A further stage in the investigation will be to determine, by audiometric tests in a suitable and adequate group of personnel, whether there is a correlation between loss of acuity and the total duration of the time during which individuals have been exposed to excessively loud noise. Meanwhile, there is much evidence from other sources that deafness of this type whether temporary or chronic, is symptomatic of physiological insult to hearing.

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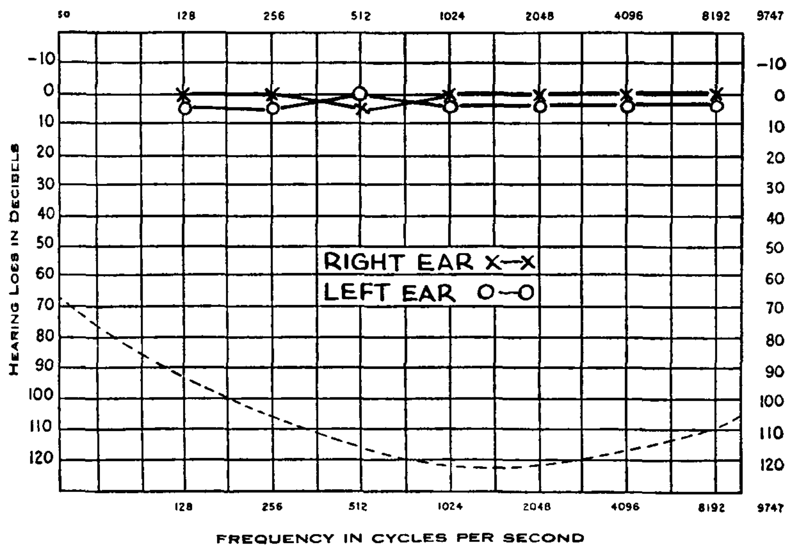
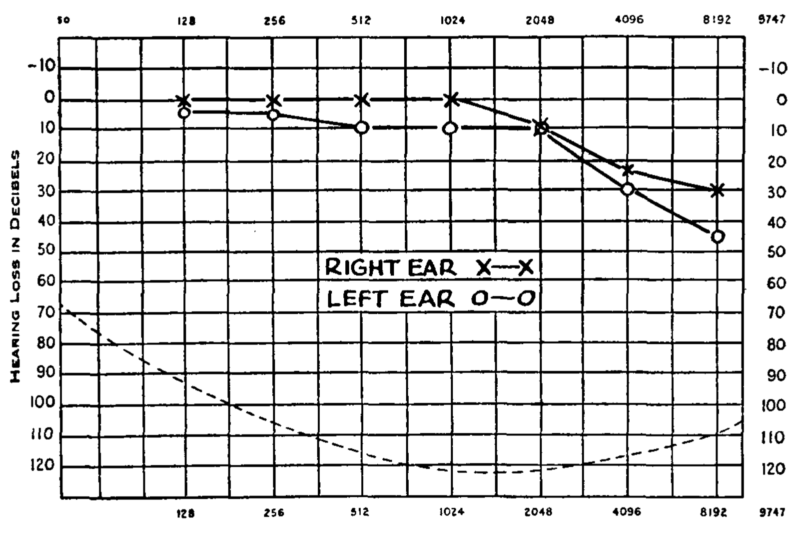
Before flight.

Audiogram of G.T.W.H. (Pilot), age 29, date 4.3.39.



Taken before flight in twin-engined bomber.

After flight.



Taken within ten minutes after landing.

Duration of flight one hour. Ears unprotected. Aircraft: twin-engined bomber. R.P.M. 1,800-2,200. Noise level: 119-123 Phons (B.S.). Left ear, nearest engine.

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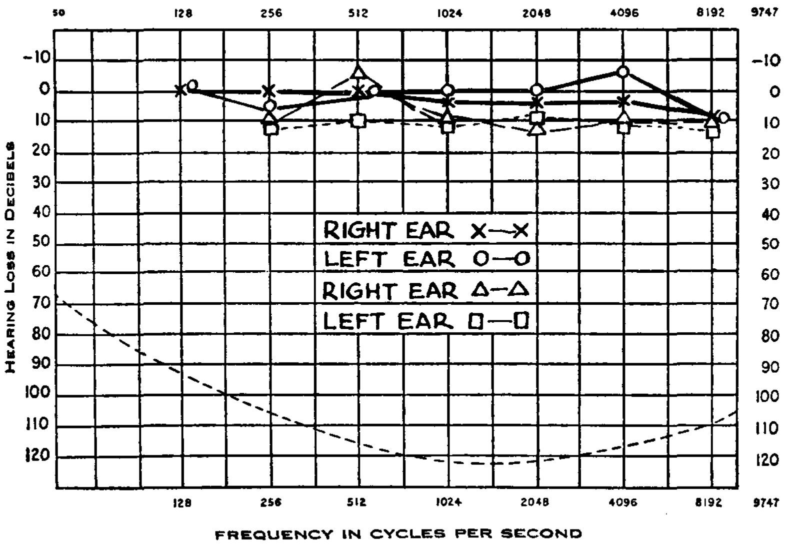
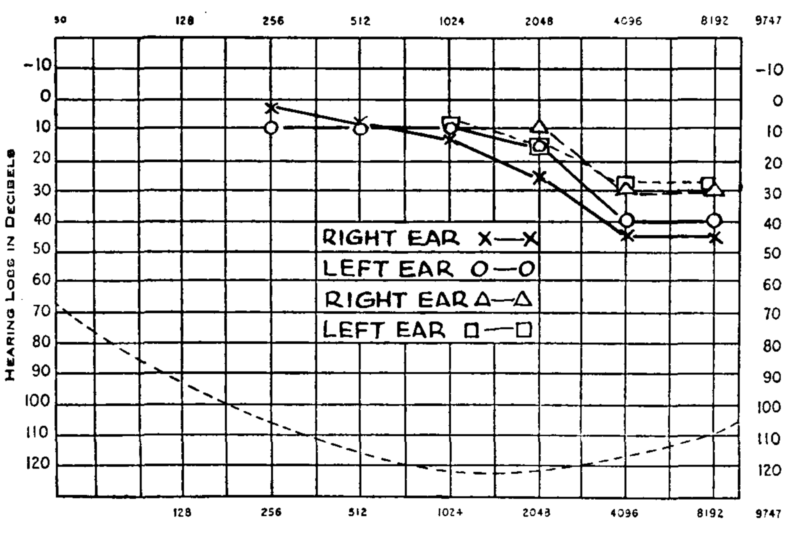
Audiogram of E.D.D.D. (passenger), age 44, date 4.3.39.

Before flight.



Taken before flight in twin-engined bomber.

After flight.



Taken within ten minutes after landing.

Duration of flight one hour. Ears unprotected. Aircraft: twin-engined bomber. R.P.M. 1,800-2,200. Noise level: 119-123 Phons (B.S.). Right ear, nearest engine.

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It is noticeable that all audiograms given by Bunch, in his important article on deafness caused by exposure to excessive noise from whatever source, have the same principal feature, bilateral diminution of acuity to upper tones with the hearing for lower tones unaffected. This holds good of all his instances, whether the deafness was ascribed to over-stimulation by continuous noise as in boiler-making and similar industries, or to impulsive sound such as that of gunfire. Many of the patients are reported to have complained of tinnitus.

Similar also in general character is the progressive diminution in acuity for higher tones which Montgomery found to have taken place in individuals free from ear disease or injury, purely as the result of increasing age.

Montgomery tested 185 individuals belonging to four age groups and showed that the diminution of sensitivity to high tones which was most marked in the eldest (aged 50-59) group, had appreciably begun in the group aged 30-39 years. The maximum hearing loss recorded by him as the mean for the age group 50-59 years was, however, significantly less than that found in the present investigation to be caused by very loud aircraft noise. Montgomery concluded that normal individuals aged 50 to 60 years would be unlikely to have conscious difficulty in hearing speech except in an auditorium.

Laboratory experiments with men and animals as subjects have hitherto been the chief source of knowledge about the frequency-intensity characteristics and the duration of sound stimuli which are dangerous to hearing or are liable to bring about undesirable subjective effects such as discomfort, tinnitus, pain, or changes in the apparent pitch and loudness of sound subsequently heard. A number of workers have reported the production of degenerative lesions in the ears of animals as the result of exposure to sound at large intensities, at frequencies ranging from C^1 to C^5 (256 to 4096 Hertz), usually over periods of many days.

Stevens and Davis have observed in animals a physiological phenomenon, which they call hysteresis or overloading, when the intensity of stimulation is increased beyond a point which can be determined with precision at many audible levels of frequency. Up to this point an increase in the intensity of the stimulus brings about an increase in the voltage of cochlear potential, but beyond it there is a diminution in the voltage.

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The view that this phenomenon of hysteresis signifies that the auditory mechanism has been exposed to physiological insult is confirmed by its association with a condition, a depressed response (subsequent to the overload), from which recovery may be prolonged over a period of hours. For example, stimulation which is 40 decibels supramaximal may reduce the cochlear potential to 30 or 40 per cent. of its original maximal value. They say that since still more violent stimulation causes disruptive effects and degenerative changes and involves temporary or permanent damage to the hair-cells, it is reasonable also to attribute the overload and hysteresis effects to the hair-cells.

Many laboratory investigations of aural fatigue in man have been directed towards finding the frequency, intensity and duration of sound which is capable of bringing about a subsequent condition of depressed response or temporary deafness. In a previous study by two of the present writers fatiguing tones, varying in frequency from C^1 to C^4 (256 to 2048 Hertz), were used at intensities up to 120 decibels above normal threshold. The loudness level was therefore comparable to that of the noise produced by some high-powered aeroplanes.

Although the duration of the fatiguing tone was usually restricted to two minutes, marked temporary losses of sensitivity led to many experiments. The greatest losses were caused by fatiguing tones 512 to 2048 Hertz. Acuity was diminished over a range of frequencies extending from the level of the fatiguing tone to about one octave higher. Considerable tinnitus was noted and recovery from the maximum amount of fatigue was prolonged over a period of hours. A varying degree of susceptibility to aural fatigue was found among the subjects, and there were even differences in susceptibility between the two ears of the same subject. Such variations in susceptibility have been observed by other workers and may possibly account for much of the difficulty which has been experienced in exploring this field.

Up to this point a critical analysis of all available knowledge leads to a hypothesis as to the causation of high-tone deafness in aviators and others as the result of exposure to very intense sound.

Further experiments are being made during the present investigation in an attempt to throw more light on the causation of traumatic high-tone deafness. Audiometric measurements of the effects of traumatic noise from every kind of source as well as the results of experiments on aural fatigue and on physiological overload in animals give a picture of high-tone deafness, as measured by both air and bone conduction, accompanied or followed in the human listener by tinnitus. Individual susceptibility varies, but as the intensity and duration of the fatiguing sound is progressively increased a succession of phenomena is revealed in all subjects. First there is an intensity value at C^3 (1024 Hertz), about 100 decibels above the threshold of audibility exposure to which for even the short period of two minutes leads to aural fatigue involving subsequent depression of response. Beyond this point prolongation of the fatiguing sound, or of the total length of intermittent exposure over a period, or further increase in its intensity, causes greater immediate loss of sensitivity and slower recovery, until temporary deafness becomes chronic. Still further increase in intensity brings about cochlear degeneration and disruption.

The nature of the problem now to be studied can be summarized as follows.

The greatest hearing losses recorded in audiometric tests by ourselves and by other workers in patients suffering from traumatic deafness are almost universally found in the frequency of C^5 (4096 Hertz). A mass of evidence has been accumulated, notably by Guilf and his collaborators, proving that serious deafness at this level of pitch is almost always associated with cochlear degeneration in the basal turn. Now aural fatigue is usually found to be greatest at or about the frequency of the fatiguing tone, but it will be seen from the following section that frequency analysis of aeroplane noise by existing methods indicates that all its components of large amplitude are low-pitched and occur below the frequency of 700 Hertz. On this basis it would appear that a low-pitched noise is causing high-tone deafness. Elucidation of this apparent inconsistency may be of importance for our understanding of the cochlear function.

3. Physical Characteristics of Aeroplane Noise

With the kind co-operation of Dr. P. T. Kerridge who placed a wave analyser at the disposal of one of us, we carried out analyses of sound in three types of aircraft. The test was

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made on the ground with the Marconi-Ekco Wave analyser. One single-engined and two twin-engined aircraft were tested.

The R.P.M. were between 1,800-2,000, and the total noise between 119 and 123 phons (B.S.).

Our measurements showed that the frequencies which gave the highest relative loudness of components was invariably at the lower end of the scale, viz. between 30 and 200 Hertz. In no case was there any component in the region of 4000 or 5000 Hertz.

Perhaps it is permissible to explain that noise in connection with flying arises from three sources :

(*a*) the engine (mechanical-exhaust),
(*b*) the propeller,
(*c*) wind (slip stream).

A note may be added about the propeller.

The note it emits is of three kinds. It consists of (1) pressure fluctuations caused by passing blades—a kind of pulse of sound ; (2) eddies thrown off by the blades as they pass the air coming mainly from the tips of the blades, where the velocity is greatest ; (3) a note the pitch of which the blade is capable and which could be excited by striking the propeller. This is caused by the twist or flutter in its motion and is seen in non-rigid types of blades. The sound is of maximum intensity in a direction to the side of and somewhat behind the propeller and is considerably less in the axis in front or behind it.

4. Investigation of Methods of Ear Protection

At the beginning of the investigation, tests were made by two of us with regard to the amount of protection given by the standard pattern of flying helmet and by certain types of ear defenders. In addition, we measured the effects of a number of simple ways of blocking the ear, such as closing the ear with a telephone receiver, insertion in it of the finger tips and closure of the meatus by light pressure on the tragus.

Later, with the collaboration of Mr. V. F. Lambert, Honorary Otologist to the Department of Education of the Deaf, Manchester University, experimental methods of packing the meatus were introduced. These consisted of simple plugs of cotton wool and plasticine and of various combinations of such methods. Some of the results are given in the table below.

The effect of the addition of liquid paraffin, to fill the meatus completely, was investigated and found to give a little more insulation than that given by the plug. The results so far indicate that it is possible to obtain 30 to 40 decibels insulation for incident sound of high frequency by means of a close fitting plug. Great insulation for sounds of low frequency (say less than 500 Hertz) is, however, extremely difficult. A point appears to have been reached at which further increase in the density of the plug does not result in much further increase in insulation.

It should be pointed out that low frequency insulation of the order of 10 to 15 decibels cannot be obtained unless the ear plug forms a good seating with the walls of the meatus. Increase of insulating power of a material with frequency is a physical phenomenon due to increase of mechanical impedance with frequency. In the tests made the insulation obtained at high frequencies due to the plugs is almost as great as that due to a single brick wall in the case of air-borne sounds. It appears probable therefore that a saturation point may have been reached in the degree of insulation obtainable by means of plugs in the meatus.

A note on the problems involved in packing the external auditory meatus by Mr. V. F. Lambert, is appended.

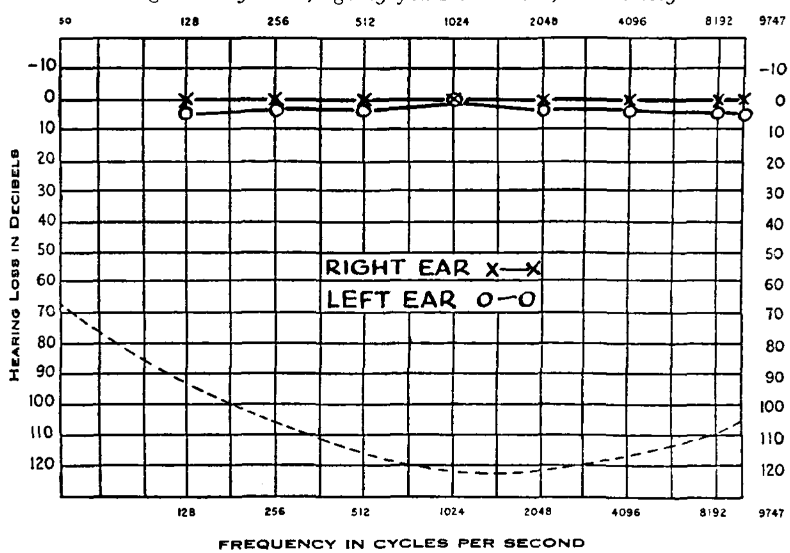
> " The finding of a method of completely occluding the meatus seemed, on first consideration, to be quite simple and straightforward but in practice this was not the case. The deeper bony portion of the meatus, being rigid, should be as easy to obliterate as it proved to be in the dried skull. Unfortunately this part of the ear passage in life is very sensitive and extremely intolerant of manipulations of any kind and particularly of any attempts at packing with a solid foreign body. Added to this is the additional factor of the very real risk of damage to the drum head by such packs. The cartilaginous meatus is more tolerant of manipulations but unfortunately it is mobile and movements of the jaw joint are easily transmitted to it, as anyone who has had a furuncle of the meatus can easily testify.
>
> Keeping in mind these initial difficulties, one had then

to try a substance for use as a pack which would be soft enough to mould into position without being so firm as to damage the drum if pushed too far into the meatus and yet soft enough to fit snugly into the passage and remain flush with its walls, despite the movements of the meatus.

Substances with a waxy base immediately suggested themselves. Ambrene, and its Army counterpart of War days—Paraffin No. 7—readily came to mind but, from previous experience of these in the treatment of radical mastoid cavities, one appreciated the difficulty of being able to introduce them in a liquid form at a temperature from which the meatus and drum would suffer no ill-effects. This method, therefore, was not tried. Stent dental wax was tried but this again was discarded because it proved difficult to introduce and, when hard in the meatus, did not fit sufficiently tightly against the wall of the passage during movements of the jaw. Plasticine, its normal consistency reduced by free admixture with vaseline, was fairly easy to mould into the ear passage but, on test, did not appear to be helpful in producing an artificial obstructive

Audiograms showing effect of protecting ears by wearing a helmet.

Audiogram of J.W.P., age 25 years 6 months, date 28.6.38.



Total hours of flying 1,620, of which 150 in enclosed cabin during last year. Has always worn a helmet closely strapped. Has never flown without one.

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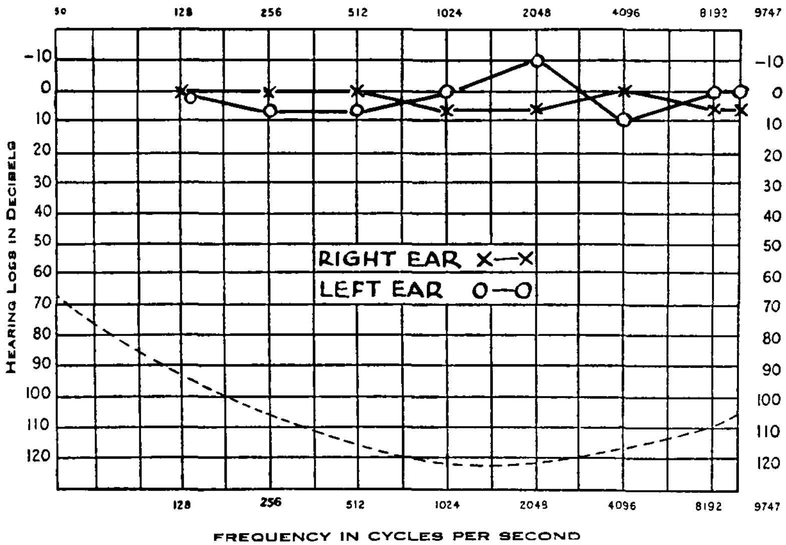
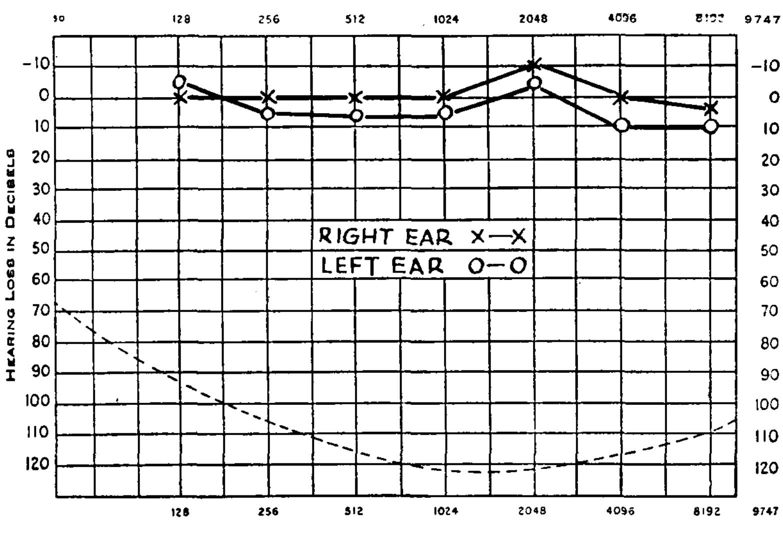
Audiogram of O.P.J., age 40, date 21.1.39.



Total flying 14,000 hours civil aircraft for last 20 years. Has always worn a helmet or protected ears until last few years when flying in enclosed cockpits. His relative position to engines is well forward.

Audiogram of J.B., age 39, date 4.3.39.



Total flying 3,050 hours. Has always worn a helmet or protected his ears. Last twelve months has flown 125 hours.

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deafness. The possibility of using a heavy fluid in a soft rubber container was tried but proved to be of no practical value.

Finally, various combinations of vaseline packs with liquid paraffin were tried with the results as shown. This method of using cotton wool smeared with vaseline proved to be a quick, safe and efficient method of packing the meatus."

TESTS OF METHODS OF EAR PROTECTION.

Methods.

1. Flying helmet firmly strapped so that the telephones and their holders closely seal the ears.
2. Ear defenders.
3. Finger tips in ear.
4. Cotton wool saturated with vaseline.
5. Liquid paraffin and cotton wool saturated with vaseline.
6. Liquid paraffin and cotton gauze saturated with vaseline.
7. Meatus packed with plasticine.

Protection stated as hearing loss in decibels.

(Measurements by air-conduction from a loud-speaker source.)

Method.	1.	2.*	3.	4.	5.	6.	7.
250	5	15	20	15	15	10	10
500	—	10 to 30	—	15	20	15	10
800	15	15 to 25	25	15	25	25	10
2,000	25	15 to 50	25	15	25	40	20
3,000	—	10 to 45	—	30	35	40	25
4,000	35	25 to 55	35	30	50	50	35

* It proved impossible to fit defenders into the ears with equal tightness in successive tests because the material of which they were made was hard and failed to adjust itself to variations in the shape of the individual meatus.

The methods of protection already tried fall therefore into two distinct categories.

The flying helmet with its telephone makes a relatively heavy and close-fitting covering over the ears as contrasted with various methods of packing the meatus.

Audiograms of personnel using a helmet of the high altitude type with the ear phones attached show no loss for high tones.

The relative position of the occupants of an aircraft to the engine and propeller appears to have some influence on the effects of noise on auditory acuity. If the occupants are placed well forward and in front of the engine the effect is considerably less marked than if sitting between or below them.

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Effects of Aeroplane Noise on Aviators

Summary

1. A loss of high tones is noted in persons exposed to aeroplane engine noise if the ears are not protected.

2. This loss becomes apparent at an early stage, even after a few hundred hours. It varies with individuals, and is temporary at first but becomes permanent after a time.

3. No deafness amounting to disability is complained of unless the speech frequencies are involved.

4. Bone conduction is diminished *pari passu* for frequencies showing a loss of air condition.

5. Wave analysis of aircraft noise, by existing methods, indicates that all the components of large amplitude are low in frequency. There is thus an apparent inconsistency with evidence obtained in experiments on aural fatigue and cochlear degeneration as the result of noise, in which depression of response has occurred at or about the frequency of the fatiguing tone.

6. Protection of the ears appears to diminish, if not eliminate the risk of impairment of auditory acuity as measured by the audiometer.

7. Various methods for protecting the ears have been studied ; investigations in this direction are still in progress.

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