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REPORT APRE-39/73 (R)

THE EFFECTS OF NOISE ON HEARING: PART I. WEAPON NOISE

by

M. A. Elwood, [redacted] P. F. Brasher RAMC

and

L. M. Croton

1973

MINISTRY OF DEFENCE
ARMY PERSONNEL RESEARCH ESTABLISHMENT
c/o Royal Aircraft Establishment,
Farnborough, Hants

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ARMY PERSONNEL RESEARCH ESTABLISHMENT

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Project No: P$00
Sponsor: DAHR, DCT
APRE File No: 406/2/09
MOD File No: 86/Research/1609

APPROVED: Alex Cassie
for Director

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FOREWORD

The work undertaken for this report was in the main completed during the years 1965-1969. The information thus obtained has been used to guide sponsors and developers, and in the design of more recent experiments. Details of some aspects of the work have been published in APRE Research Memoranda S/3 (Brasher, Coles, Elwood and Ferres, 1970) and T/1 (Elwood, Brasher and Croton, 1970). This report is however the first in which the bulk of the work is described.

The final form of this report has been prepared by Mr M R Forrest, on the basis of an original draft by Dr M A Elwood and co-authors.

A report on steady-state continuous noise, with particular reference to noise in armoured fighting vehicles, is in preparation under the terms of Project 500. Current APRE Projects 528, 559, and Research Study R32 are relevant to the subject matter of Project 500.

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ABSTRACT

The effect of impulsive (gunfire-type) noise on exposed personnel has been assessed by measurement of temporary hearing threshold shifts (TTS), for a variety of weapon systems. Physical characteristics of the noise sources used are given, together with results of a detailed study on TTS arising from the noise of the self-loading rifle (SLR). The variation in sensitivity of exposed personnel to different impulsive noise sources, or to the same source (SLR) on different occasions, is described.

It is shown that adequate ear protection against the noise of weapons currently in service can, in the majority of cases, be provided by the 'Sonex' ear plug; the exceptions, for which more effective ear protection is required, are identified. Recommendations are made for a hearing conservation programme for use with existing or developing weapon systems. Requirements for further research are discussed.

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INTRODUCTION

1. The Director of Army Health requested a study of noise in the British Army and its effects upon the hearing of personnel. The preliminary results of the noise survey have been given (1) in terms of limiting numbers of rounds for impulsive noise and exposure times for steady state noise produced by specific weapons and vehicles. The present report covers in detail the effects of impulsive noise upon hearing.

2. Where noise is characterized by a sharp rise to a transient peak pressure, which decays with or without subsidiary oscillations within a short period of time, it is known as impulsive noise. This is in contrast to steady-state (continuous) noise which can be defined in terms of pressure oscillation at given frequencies and intensities over relatively long periods of time.

3. Since the noise sources were weapons it is important to clarify the relation between impulsive noise and blast. Impulsive noise as defined above includes blast, as well as shock waves, sonic booms, and some industrial machinery noise. Although the weapons may have produced shock waves from the projectiles fired, the primary noise source was muzzle blast, and in some instances subsidiary pressure pulses or oscillations associated with reflections from surrounding surfaces or with the operation of the gun mechanism.

4. After exposure to intense noise of either impulsive or steady-state type, there is often deterioration of hearing ability. This may be accompanied by any, all, or none of the following subjective symptoms; pain, dullness of hearing, and ringing in the ears. Since hearing can deteriorate in their total absence none of these symptoms can be used as a reliable index of the hazard. However, if any noise does produce such symptoms it would be wise policy to wear ear protection until such time as the exposure can be evaluated.

5. Decay in hearing ability is experienced in two forms. There may be some temporary threshold shift (TTS) which will recover with time. If the exposure has been sufficiently intense, or has been repeated without sufficient time for recovery of temporary changes, then permanent threshold shifts in hearing (PTS) may be expected. After exposure to steady-state noise, any TTS experienced will depend upon the frequency content of the noise source, and in general may be expected to be one half to a whole octave above the predominant frequencies in the noise source. A similar relationship does not appear to exist for impulsive noise, possibly because it is difficult

and time consuming to identify the frequency content of short pulses. The temporary or permanent change in hearing resulting from mixed impulsive and steady-state noise requires further study.

6. The decay in hearing ability results from damage to the hair cells in the organ of Corti in the cochlea; it is thus sensorineural in nature, and sometimes difficult to distinguish from other sensorineural losses. Damage to the ear drum, although not unknown where high pressures are involved, is not the typical damage mechanism nor generally as serious as the damage to the hair cells.

7. The extent of permanent damage to hearing caused by weapons was very ably described by Murray and Reid (2, 3) in 1946. Most armed forces in the world have experienced the effects of weapon firing upon their personnel. Some have in fact instituted programmes of hearing conservation, stimulating an increased awareness of the situation, and improvements are anticipated.

8. The aim of the present study was to measure the noise exposure of personnel in the British Army, and to assess the changes in hearing which result. The present report deals with the effects of gun fire, and relates the results to published damage risk criteria. Exposures to steady-state noise will be covered in a future report (4).

DAMAGE RISK CRITERIA

9. When the present study was first initiated, there was no agreed criterion against which the hazard of impulsive noise to the inner ear could be assessed. Since that time laboratory and field work has been evaluated and a provisional damage risk criterion (DRC) has been published jointly by British and American authors (Coles, Garinther, Hodge and Rice 5, 6, 7). These papers define impulsive noise and require measurements of the peak transient pressure level, the pressure-wave duration or A-duration and the pressure-envelope duration or B-duration. The A-duration is the time required for the initial or principal pressure wave to rise to its positive peak and return momentarily to ambient. The pressure envelope duration or B-duration is the total time taken for the envelope of the pressure fluctuations (positive and negative) to decay by 20dB from the peak pressure level. The figures illustrating the definitions of these authors are reproduced in Figures 1 and 2.

10. The original damage risk criterion adopted by these authors (5, 6, 7) was the protection of 75% of the population to the limits defined previously for steady-state noise exposures in the CHABA steady-state noise DRC (8). These were that the Temporary Threshold Shift in Hearing two minutes after exposure, TTS_2, which is believed to be equivalent to or in most cases greater than the likelihood of the eventual PTS from recurrent exposure, should not be more than 10dB at or below 1000 Hz, 15dB at 2000 Hz and 20dB at or above 3000 Hz.

Fig. I

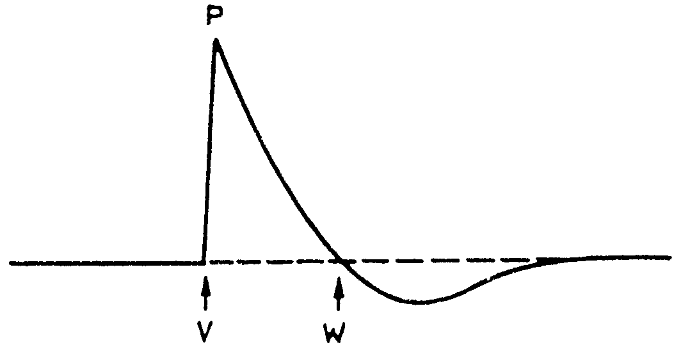
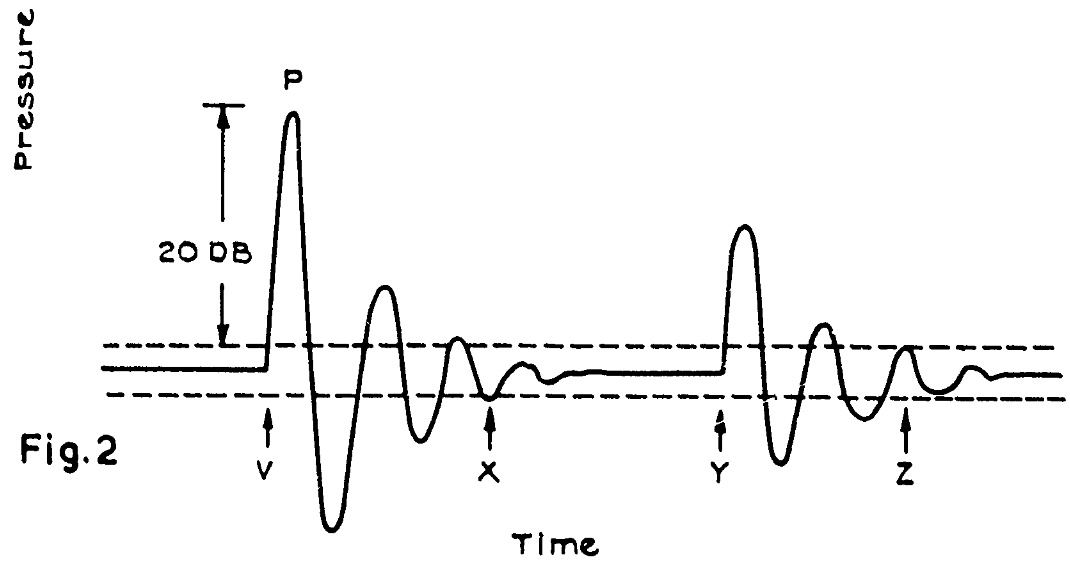


Fig. 2



Two principal types of impulsive noise, after Ward (9)

Fig. I Idealised transient pressure pulse (VW=A Duration)

Fig. 2 Diagrammatic transient pressure pulse with subsidiary pulse, both showing subsequent oscillations (VX+YZ = B Duration)

11. These limits of pressure and duration were re-defined by CHABA Working Group 47 to give protection to about 95% of men when the pressure pulse entered the ear directly at normal incidence [9] (see Figure 3). In this way the worst exposure is defined, with permissible corrections for less hazardous situations. The resulting relation between A- and B-durations and maximum peak pressure is shown in Figure 4.

12. The CHABA Working Group have suggested several modifications of their DRC for certain practical situations:

(a) Protection of approximately 75% of men can be made by permitting an increase in pressure levels of 5dB.

(b) Protection of the most susceptible persons exposed to impulsive noise may require a reduction of the protection limit by 5dB or occasionally even more.

(c) Where the impulses pass the ear at grazing incidence, the protection curves may be increased by 5dB. It is important that the pressure level be measured at grazing incidence.

(d) The DRC and its limits are appropriate to about 100 rounds per day, and a correction factor appropriate to numbers of impulses varying between 1 and 1000 is suggested and is reproduced in Figure 5.

13. Coles et al [7] suggest that an allowance of 20 to 35 dB be made for the effect of ear protection; the lower figure referring to ear plugs and the higher to the more effective types of ear muff. The degree of protection actually obtained will depend on how well the ear protector fits and on the nature of the impulsive noise as well as on the type of protector used.

METHOD

General

14. The techniques used in the present study fall under the following main headings:

i. Measurement of impulsive noise in terms of peak pressure and also A- and B-duration.

ii. Measurement of TTS resulting from exposure to impulsive noise. The majority of these exposures (listed in Table XIX) were conducted using "Sonex" ear plugs as hearing protection, as in these cases the hazard to unprotected hearing was thought to be unreasonably high.

iii. A detailed survey of the effect on unprotected hearing of the noise of the self-loading rifle.

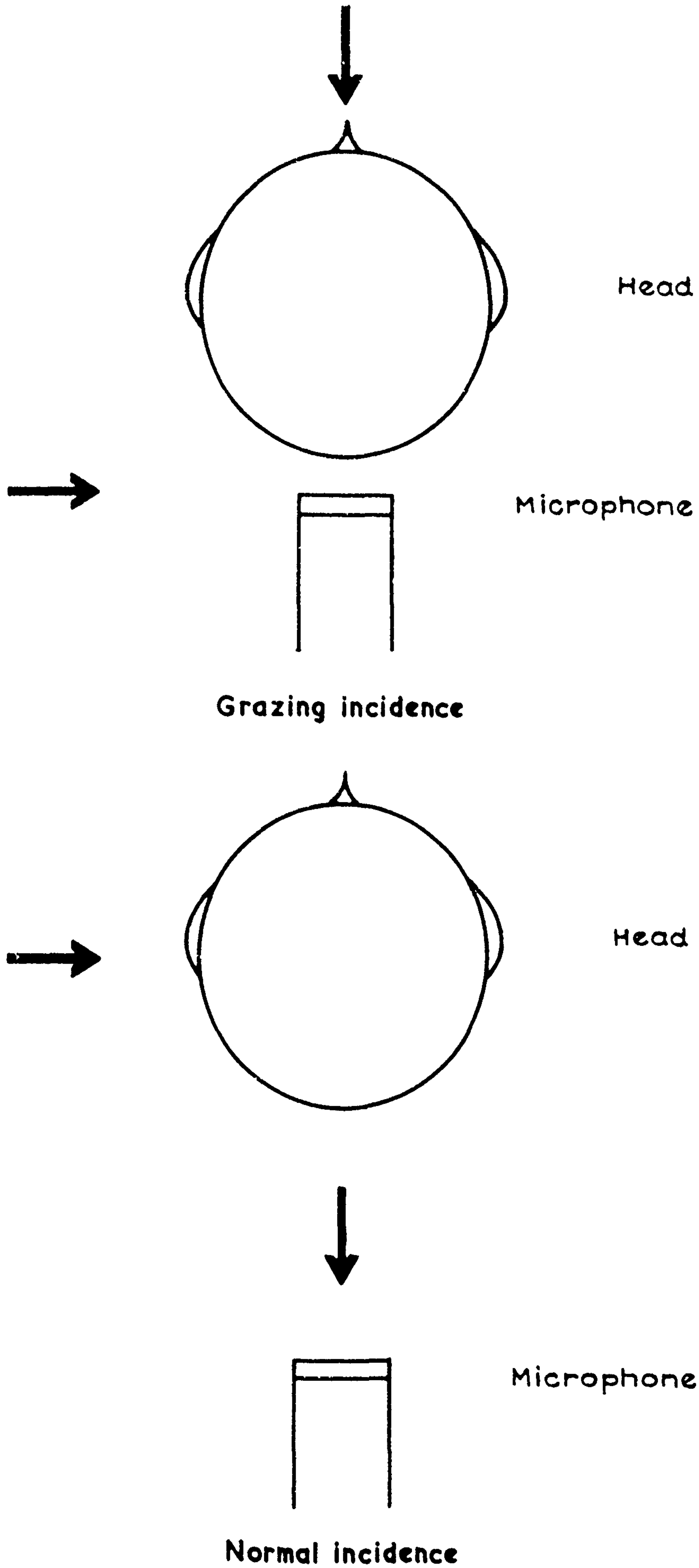

Head
Microphone
Grazing incidence
Head
Microphone
Normal incidence

Fig.3

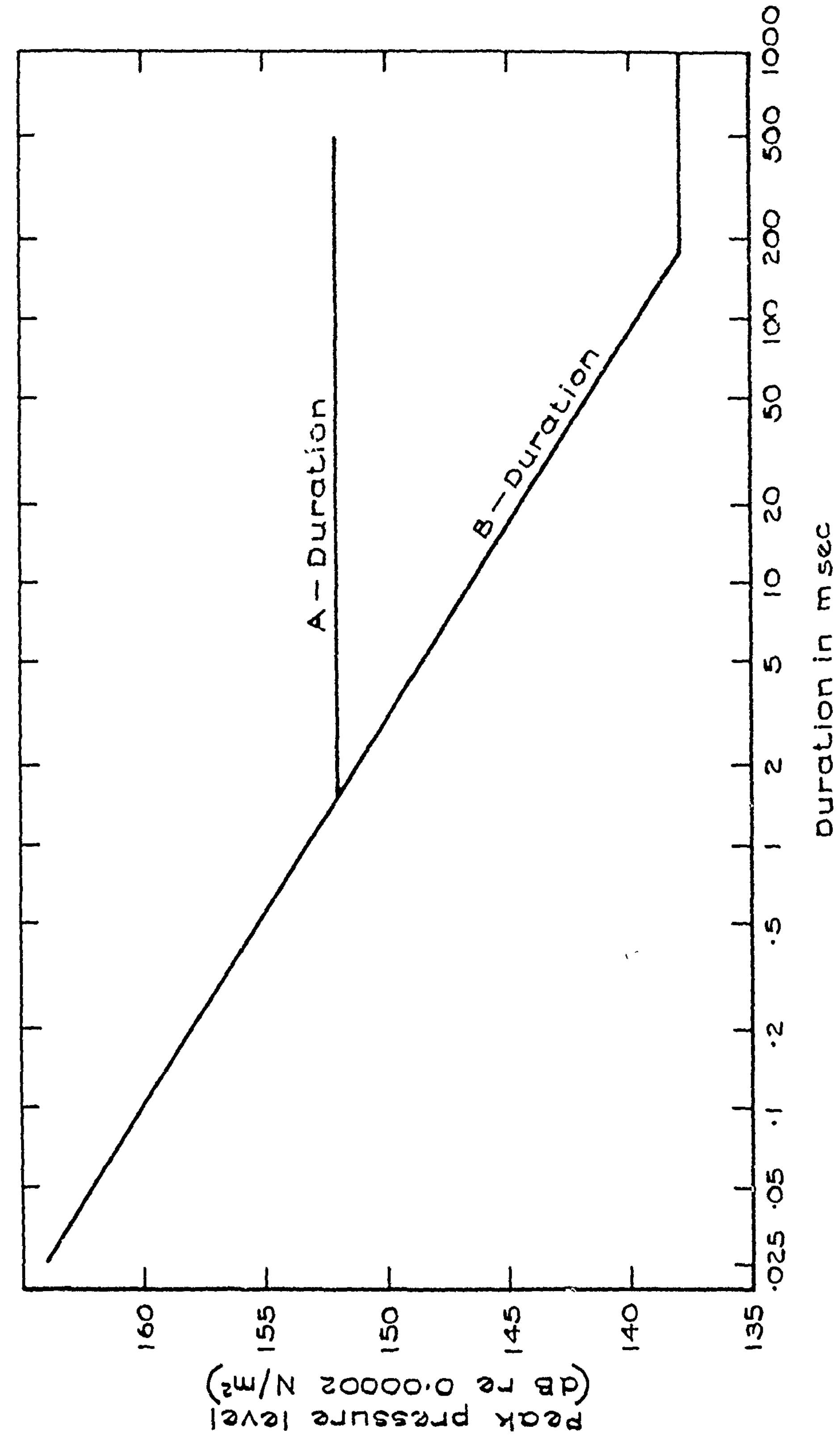


Fig. 4 Basic limit for 95% of unprotected ears exposed at normal incidence to impulsive noise after Ward (9)

Figure 4

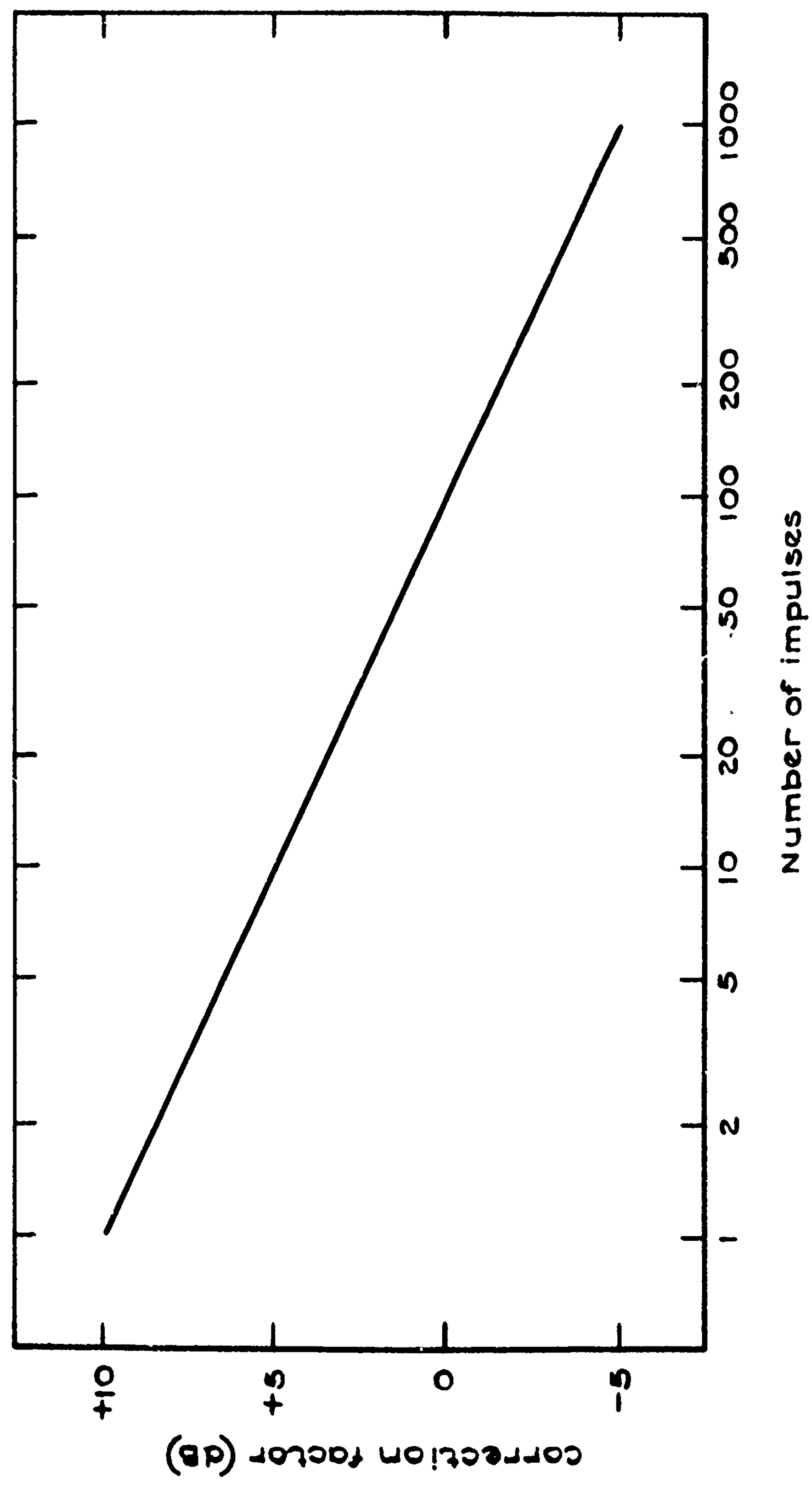


Fig.5 Correction factor for number of impulses per day, after Ward (9)

Figure 5

15. The above techniques are of course complementary. Physical measurements of the noise allow comparison of TTS results between different weapons of similar noise characteristics, and prediction of the hazard to hearing from other weapons for which only physical noise measurements are available. The detailed survey of (iii) above throws light on the more limited results under (ii).

16. A study was also conducted on the influence of middle-ear muscle activity on TTS. This study has been reported elsewhere (10) and will not be further considered here.

The Measurement of Impulsive Noise

17. Measurements of impulsive noise were made using three distinct systems. The first two of these required highly skilled personnel, and complex and sophisticated equipment. The other technique used a simple peak reading meter which could be used by less qualified range staff in routine measurements. There is no ideal transducer available, but distortion can be kept to a minimum when suitable gauges or microphones are used in specific situations.

18. The cooperation of the Chief Superintendent of Ranges (Army) provided measurements of peak pressures associated with most army weapons using round baffle blast gauges. The output from these gauges was fed through amplifiers to high speed drum cameras. The pressure time histories obtained could resolve time differences of the order of 1 millisecond, and pressure ranging from 30 psi to 1 psi and with less accuracy to 0.1 psi. These blast gauges were direction sensitive and therefore presented problems of orientation when used in situations where reflection from the surroundings were expected. They were oriented at grazing incidence to measure the peak hydrostatic pressure. It was usually possible to position these gauges such that the pressure pulse reflected from the ground also passed the gauge at grazing incidence.

19. It is possible that the use of blast gauges led in some cases to an under-estimation of the B-duration, as their relatively low sensitivity and resulting small trace excursion might have caused pressure variations 20dB below the peak to be missed. It is possible also that in the case of rifle noise their relatively slow rise time, a result of the physical size of the sensitive face, might have led to a slight under-estimation of the peak pressure. This is not to be seen as a criticism of the gauges, rather as an admission that they were being used for purposes for which they had not originally been designed.

20. Using small omnidirectional microphones, the University of Southampton and the Institute of Naval Medicine have been able to measure peak pressure levels associated with weapon firing (5, 7). The output from the microphones was fed to a storage oscilloscope and the trace photographed. Pulse duration to a few micro-seconds, and peak pressures up to approximately 5 psi (185dB re 2×10^{-5} N/m^2) were measured. Although the microphones were described as omnidirectional, they were used at grazing incidence for the measurements reported here.

21. APRE evaluated a simple impulsive noise meter developed by DAWE Instruments Limited, (Type 1412 A), used with an omnidirectional microphone, as a means of making routine measurements. The output of the microphone was stored in a capacitance circuit which retained the nominal peak within one decibel for nine seconds. The circuit could also be used to give some indication of the pulse duration. The meter was originally designed for use in industry, and unfortunately proved unsuitable for the very fast rising pulses associated with weapon firing.

22. The units of measurement used were of two kinds. For blast measurement the pound per square inch (psi) is the more usual unit. Noise measurements have usually been referred to an absolute pressure level of 0.0002 dynes per square centimeter and a ratio scale in decibels (dB) constructed upon it. By international agreement $dynes/cm^2$ has been replaced by the Newton per square meter (N/m^2). Since 10 $dyne/cm^2$ equals 1 N/m^2 (ie 1 Pascal), units in dB reference to 0.0002 $dyne/cm^2$ and to 0.00002 N/m^2 are the same. Conversion from psi to dB is a relatively simple calculation according to the formula -

$$y \text{ in psi} = (170.77 + 20 \log_{10} y) \text{ dB}$$

Audiometry

23. The majority of this work was conducted on remote firing ranges where the background noise levels could be as low as 30dB and were never above 50dB. In these circumstances the use of audiometric booths was found to be unnecessary, and adequate attenuation could be provided by simple padded hoods constructed of expanded rubber and measuring 2 ft x 2 ft x 2 ft. These are illustrated in Figure 6.

24. Amplivox Model 51 screening audiometers were used for the majority of the audiometric tests, since they were battery operated and convenient for use on remote ranges. Where power was available some subjects were tested with the Rudmose ARJ-4 Audiometer. All the audiometers were calibrated to British standard zero (BS 2497 : Part 2 : 1969) (11), and with the kind cooperation of the Institute of Naval Medicine were jointly calibrated with their audiometers. In this way the audiometric work in the two services was placed on a common calibration system, which was rechecked at six monthly intervals. This was considered adequate for the study of temporary threshold shift.

The Sensitivity to Impulsive Noise

25. The hearing levels of 155 subjects were monitored before and after a maximum of three consecutive exposures to impulsive noise. Withdrawal of the more sensitive subjects was made dependent upon their response to the earlier exposures. The higher frequencies were tested in the following order: 6, 4, 3 and 8 kHz, commencing with the more exposed ear two minutes after the last shot. When a TTS of 20dB or more in either ear at any frequency tested, or two changes of 15dB at two different frequencies occurred, the subject was withdrawn. The double 15dB criterion was used after preliminary tests revealed in some cases a subsequent large TTS with further exposure. This was not consistent, however.

Figure 6

26. A standard exposure of 160dB at the ear was produced by an SLR in the main sensitivity test. For the comparative series single pulses were obtained from an infantry support weapon providing a series of pressures from 171 to 185dB at appropriate distances, and an HE Charge which was made available to the authors at ERDE, and was described by Hawkins and Hicks (1966) (12). The peak pressure levels are given in Table I.

TABLE I

CHARACTERISTICS OF NOISE SOURCES USED IN THE COMPARISON OF SENSITIVITY

	Rifle[1]	Infantry Support Weapon	HE Charge[2]
Peak Pressure Level dB	160	171 to 185	160
A - Duration millisec	0.25	2	5
B - Duration millisec	12	N/A	18

Notes 1. From Coles et al (1968) (5, 6, 7)
2. From Hawkins and Hicks (1966) (12)

27. The number of rifle shots used was determined after preliminary tests had revealed very low TTS after 1, 5 and 10 rounds. However it would be wise to include a single or five round section, if the test were to be used on subjects unaccustomed to rifle noise. Rounds were fired at five second intervals on a verbal command audible to the subjects. Therefore the results are appropriate to the sensitivity of forewarned men. The timetable is given in Table II. Recovery audiograms were taken as necessary. A verbal command was used to forewarn subjects exposed to the infantry support weapon, but the HE Charge was fired at a random interval of 10 to 15 seconds after a verbal forewarning to the men.

TABLE II

SCHEDULE OF RIFLE TEST

TIME (minutes and seconds	EVENT
Zero to 15.00	Pre Exposure Audiogram
15.00 to 16.35	Exposure to 20 Rounds
16.35 to 24.35	Test Audiograms - Withdrawal if indicated
25.00 to 27.30	Exposure to a further 40 Rounds
27.30 to 33.30	Test Audiogram - Withdrawal if indicated
34.00 to 38.00	Exposure to a further 60 Rounds
38.00 to 46.00	Final Audiogram

28. For the main sensitivity test 155 young men acted as subjects. They were clinically examined, all wax was removed from the ears and no ear protection was worn. A few men were excluded as their existing hearing levels indicated that unprotected exposures were unwarranted.

29. Preliminary experiments indicated that the sensitivity to impulsive noise might be very much more variable than the response to steady-state noise. It soon became evident that a single noise source was impracticable, since any source sufficiently intense to produce temporary hearing responses in the least sensitive men, would have produced unacceptably high TTS in the more sensitive men. Therefore it was decided to increase the exposure progressively, monitoring the changes in hearing levels during a schedule of rifle firing (see Table II).

Protected Exposure to Army Weapons

30. There was little point in providing further evidence that weapon firing was a hazard to unprotected hearing. The majority of exposures to army weapons were therefore conducted with the men wearing their issued ear plugs. These were fitted under medical supervision, and the fit checked by verbal communication. The fit and attenuation were not tested with audiometric signals.

31. Pre and post-exposure audiometry was conducted in the same manner as for the sensitivity test. To save ammunition, the bulk of the tests were conducted using existing training programmes for the various army weapons.

Ear Protection

32. The Sonex (V51R pattern) ear plug, illustrated in Figure 7, is the normal Service issue. At the time of this study, only three sizes were available. The attenuation of these ear plugs against pure tones (after Burns (1968) (13) is given in Table III. An indication of the required proportion of sizes is given in Table IV.

TABLE III

ATTENUATION OF V51R EAR PLUGS
(After Burns (1968) (13))

	Frequency Hz							
	63	125	250	500	1000	2000	4000	8000
Attenuation, dB	11	13	15	18	22	27	32	29

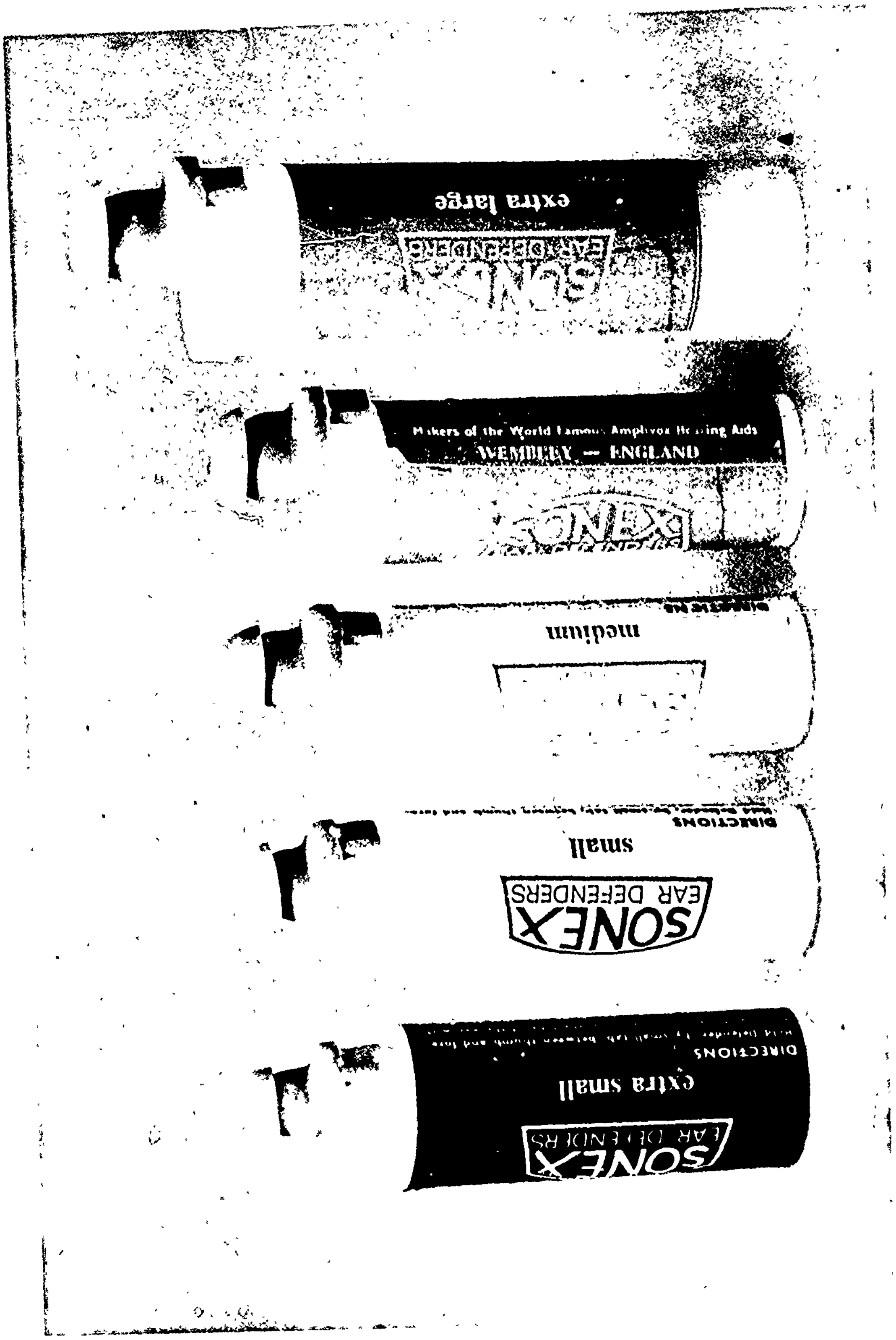

extra large
SONEX
EAR DEFENDERS
WEMBLEY — ENGLAND
medium
small
SONEX
EAR DEFENDERS
DIRECTIONS
extra small
SONEX
EAR DEFENDERS
DIRECTIONS

Figure 7

TABLE IV

PROPORTIONS OF EARS FITTED BY V51R (SONEX) PLUGS

Size of plug required	Extra Small*	Small	Medium	Large	Extra Large*
Percentage of ears	0.4	15.7	33.1	49.2	1.7

Size of sample 121 men (242 ears)

*These sizes were not available for the study and the results are estimates from the one ear too small for the existing small size, and four too large for the existing large size.

33. Although the "Sonex" ear plug was the only type of ear protector to be evaluated by extensive TTS measurements, limited experience was gained with several other types. The most effective of these was the RAF Mk III (Amplivox 16400) ear muff; its attenuation is shown in Table V (after Wheeler (1968) (14)). An earlier (Denis Ferranti) version of the RAF Mk III gave a similar degree of protection. Both muffs are illustrated in Figure 8.

TABLE V

ATTENUATION OF RAF Mk III (Amplivox 16400) EAR MUFFS
(After Wheeler (1968) (14))

	62.5	125	250	500	1000	1500	2000	3000	4000	6000	8000 Hz
Mean Attenuation, dB	16.8	19.3	25.5	32.4	38.3	38.0	34.6	42.6	43.8	36.5	31.0
Standard Deviation, dB	5.7	6.7	5.3	4.0	7.2	5.7	8.2	5.1	6.7	6.4	6.7
Quartiles	)12.5	15.0	21.2	28.6	31.2	33.7	27.5	38.7	38.6	29.6	25.4
	)22.0	26.5	29.6	35.0	45.0	43.5	45.0	48.7	48.7	40.4	35.8

34. Some other types of ear "protector" tried, such as obsolescent communication headsets and the ubiquitous cotton wool, give relatively little protection. A more satisfactory alternative for the latter item is commercially available "glass down". The relative merits of plugs, muffs, cotton wool and "glass down" are discussed by Rice and Coles (1966) (15).

35. The most interesting form of hearing protection to be tried was the "ERDEfender" ear muff. This was essentially a normal ear muff with the addition of a microphone, peak-limiting amplifier and telephone mounted on each ear cup. A battery housed on the headband provided power for the amplifier. The intention was that sounds of moderate intensity, eg speech, should be relayed to the ears by this electroacoustic chain. Intense noises, such as gunfire, would be

Figure 8

clipped by the amplifier so that the ear would be sheltered by the attenuation of the muffs. From a purely acoustic point of view, the device worked quite well, and it achieved considerable publicity.

36. Practical experience with the ERDEfender showed that the ability to hear almost normally was much appreciated by its users, and such TTS measurements as were obtained showed that the protection against impulsive noise was probably adequate. However, it was soon apparent that the device was not sufficiently robust for Service use. One of several weak points in the design was that the microphones would not stand up to the noise of heavy gunfire! In addition to this, it was a bulky and expensive item. Another ear defender based on the same principles - the Cosmocord A9000 headset - has been designed taking these factors into account, but has not been evaluated in the course of the present study. Both devices are illustrated in Figure 9.

37. Another interesting form of hearing protection which received some attention during the present study was the "Gunfender" ear plug, which achieves the same effect as the "ERDEfender", but by purely acoustic means. The evaluation of this device has been described elsewhere [16, 17, 18].

RESULTS

Pressure Measurements

38. The peak transient pressure level measured at the ear position of fi ers or instructors varied between 150 and 190 dB (0.1 and 10 psi) and was reasonably consistent between microphones and blast gauges when measurements from both were available. The data has been tabulated according to type of weapon in Tables VI-X along with pulse decay time (see para 9 above). The pulse durations were difficult to measure in some cases, and only approximate information can be given, particularly when the microphone and oscilloscope were used for the very high pressure levels associated with the 84mm Carl Gustav and 120 mm Wombat recoilless guns. Divergence between the duration results obtained with directional blast gauges and those from microphones was evident at the relatively low pressure levels around small arms. When blast gauges were used at low pressure levels, the duration could not be determined accurately.

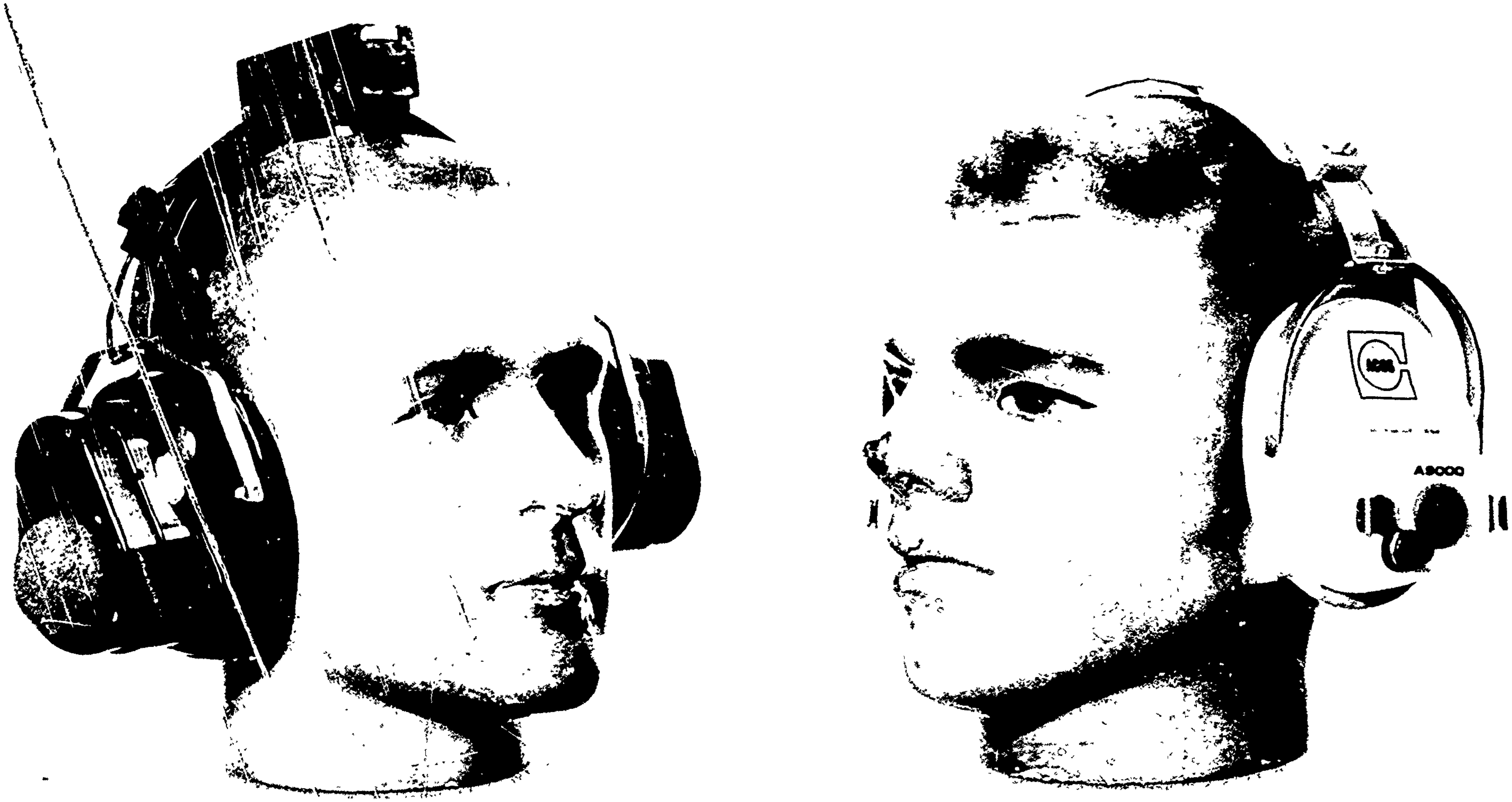


Figure 9

TABLE VI

MEASUREMENT OF PEAK PRESSURE (dB re 2 x 10^{-5} N/m^2) AND PULSE B-DURATION (millisecond)

ROYAL ARMOURED CORPS WEAPONS

Weapon/Ammunition	Pressure Transducer*	Position: Instructor on Rear of Turret dB	ms	Commander Head Out dB	ms	15 yds to one side dB	ms	30 yds to one side dB	ms	Measuring Agency and Reference
Chieftain, 120 mm gun Practice APDS or DS/T	B	171	12.5	171	13.5	173	8.5	164	9.0	P & EE(S) (19)
Service APDS		171	8.5	171	8.5	175	9.5	166	8.5	
HESH		164	10.5	165	7.0	160	6.5	160	7.0	
Centurion, 105 mm gun Practice APDS (+5° elevation)	B	167	4.5	172	6.0	-	-	163	4.5	P & EE(S) (19)
Service APDS (+5°)		166	9.5	166	7.0	174	6.5	166	7.0	
Practice HESH (+5°)		160	11.5	164	3.0	161	4.0	159	3.5	
Service HESH (+5°C)		167	5.0	165	2.5	164	3.0	159	3.6	
Practice DS/T (-3°30')		166	7.5	178	8.5	172	5.0	164	5.0	

TABLE VI (cont'd)

Weapon/Ammunition	Pressure Transducer*	Position								Measuring Agency and Reference
		Instructor on Rear of Turret		Commander Head Out		15 yds to one side		30 yds to one side		
		dB	ms	dB	ms	dB	ms	dB	ms	
Saladin, 76 mm gun HESH	B	165	8.0	172	8.5	164	9.0	157	4.5	P & EE(S) (19)
HE		164	6.0	170	8.0	161	5.0	155	4.5	
FOX, 30 mm cannon Practice ET	M	156	18.0	149	(Head In) 80	20ft to one side 165	10	–	–	APRE

Note: * B = Blast Gauge
M = Microphone

TABLE VII

MEASUREMENTS OF PEAK PRESSURE (dB re 2×10^{-5} N/m^2) AND PULSE B-DURATION (millisecond)
ROYAL ARTILLERY WEAPONS

Weapon/Ammunition	Pressure Transducer*	Position	Peak Pressure dB	Duration m sec	Measuring Agency and Reference
Gun SP 175mm Charge 3 QE 10.5	B	Mounted Crewmen:			P & EE(S) (19)
		left	166	3.0	
		right	166	3.5	
		Ground Crew (relative to trunnions):			
		1 ft back 10 ft to side	166	6.0	
		1 ft back 24 ft to side	166	6.0	
		level 43 ft to side	167	7.5	
		13 ft back 75 ft to side	162	6.0	
		15 ft back 4 ft to side	160	7.0	
		8 ft fwd 8.5 ft to side	169	6.5	
		33 ft fwd 26 ft to side	180	9.0	
		33 ft fwd 40 ft to side	166	7.0	
Gun Pack Howitzer 105 mm Charge 7 (pulse duration estimated)	B	No 1 Between Trails	176	) 3**	P & EE(S) (19)
		Layer	183	)	
		Breech Number	182	)	

Notes: 1 * B = Blast Gauge
2 ** = Estimated values

TABLE VIII

MEASUREMENTS OF PEAK PRESSURE (dB re 2 x 10^{-5} N/m^2) AND PULSE B-DURATION (millisecond) INFANTRY SUPPORT WEAPONS (in the open or ground mounted)

Weapon/Ammunition	Pressure Transducer*	Ear Position										Measuring Agency and Reference
		Firer or Layer		Loader		Instructor or Adjacent Personnel						
						4ft to side		10ft to side		20ft to side		
		dB	ms	dB	ms	dB	ms	dB	ms	dB	ms	
Mortar 81 mm, QE 45°	M	181–183	7–11	174–186	7–8	–	–	–	–	–	–	APRE
L16/Charge 5: QE 45°	B	187	3.0	–	–	182	3.6	173	4.0	165	3.8	P & EE(S) (19)
QE 75°	B	183	2.7	–	–	183	2.9	170	4.4	166	4.2	P & EE(S) (19)
	B	182	–	181	–	–	–	–	–	–	–	MVEE (20)
Mortar 3 inch: HE Mk 7: QE 45°	B	169	1.4	–	–	179	2.6	169	3.9	164	3.7	P & EE(S) (19)
QE 75°		181	1.8	–	–	181	1.7	171	3.5	164	2.9	
Mortar 2 inch: /Para. Illuminating Mk 2/2 QE 45°	B	164	0.9	–	–	160	0.8	153	0.9	–	–	P & EE(S) (19)
		170	0.9	–	–	161	0.9	153	0.7	–	–	
Gun, RCL, 84mm, Carl Gustav: /Practice A/T	M	183	8.0	187	8.0	–	–	182	8.0	172	8.0	INM (21)
Rocket Launcher 3.5 inch /Practice M29 Mk2 HE	B	168	2.6	–	–	163	3.2	160	3.4	154	6.0	P & EE(S) (19)
Gun 120mm A/T Bat	B	184–182		–		–		–		–		BRS

		182										
QE 75°	B	183	2.7	–	–	183	2.9	170	4.4	166	4.2	P & EE(S) (19)
	B	182	–	181	–	–	–	–	–	–	–	MVEE (20)
Mortar 3 inch: HE Mk 7: QE 45°	B	169	1.4	–	–	179	2.6	169	3.9	164	3.7	P & EE(S) (19)
QE 75°		181	1.8	–	–	181	1.7	171	3.5	164	2.9	
Mortar 2 inch: /Para. Illuminating Mk 2/2 QE 45°	B	164	0.9	–	–	160	0.8	153	0.9	–	–	P & EE(S) (19)
		170	0.9	–	–	161	0.9	153	0.7	–	–	
Gun, RCL, 84mm, Carl Gustav: /Practice A/T	M	183	8.0	187	8.0	–	–	182	8.0	172	8.0	INM (21)
Rocket Launcher 3.5 inch /Practice M29 Mk2 HE	B	168	2.6	–	–	163	3.2	160	[illegible].4	154	6.0	P & EE(S) (19)
Gun 120mm A/T Bat	B	184–182	–	–	–	–	–	–	–	–	–	BRS
Gun 120mm A/T Wombat L6/ Practice SH, L18 A4	M	–	–	–	–	–	–	–	–	180	35**	INM (21)
						30ft to side		40ft to side		60ft to side		
						177	35**	174.5	35**	174	35**	

Note: * B = Blast Gauge
M = Microphone

TABLE IX

MEASUREMENTS OF PEAK PRESSURE (dB re 2×10^{-5} N/m^2 AND PULSE B-DURATION (millisecond) INFANTRY SUPPORT WEAPONS (Vehicle Mounted on FV432)

Weapon/Ammunition	Pressure Transducer*	Ear Position: Firer or Layer dB	Firer or Layer ms	No. 2 db	No. 2 ms	Driver db	Driver ms	Measuring Agency and Reference
Mortar 81mm /Charge Super	M	185–169	11 to 15	167–161	–	–	–	APRE
	B	186–172	–	185–173	–	–	–	MVEE (20)
Gun RCL 84mm Carl Gustav /Practice A/T:	B	186	–	185	–	–	–	MVEE (22)
Firing Forward	B	168–183	–	174–184	–	161–169	–	P & EE(S) (19)
Firing Rearward	B	171–188	–	181–183	–	178–180	–	P & EE(S) (19)
Gun A/T 120mm Wombat:	M	187	20**	–	–	176 (QE Min) 162 (QE Max)	–	INM (21)

Notes 1. * B = Blast gauge
M = Microphone

2. ** Approximate readings. Pulse durations measurements in confined spaces are very difficult to obtain and interpret.

TABLE X

MEASUREMENTS OF PEAK PRESSURE (dB re 2 x 10^{-5} N/m^2) AND PULSE B-DURATION (millisecond) INFANTRY WEAPONS (Small Arms in the Open)

Weapon/Ammunition	Pressure Transducer*	Ear Position								Measuring Agency and Reference
		Firer		Instructor or Adjacent Firer						
				1ft to side		4ft to side		10ft to side		
		dB	ms	dB	ms	dB	ms	dB	ms	
SLR 7.62 mm (live	M	160	5.0	–	–	–	–	–	–	ISVR (5), HEL (6)
1ft above ground	B	151	0.9	169	0.5	160	0.5	155	0.5	P & EE(S) (19)
5ft above ground	B	154	0.5	158	0.5	–	–	154	0.5	P & EE(S) (19)
Blank	M	150	10	–	–	–	–	–	–	ISVR (4)
Plastic Round	M	153	10	–	–	–	–	–	–	ISVR (4)
SMG 9mm (live)	B	157	1.0	162	1.0	154	0.5	151	0.5	P & EE(S) (19)
Colt Armalite 5.56 mm AR15	B	151	1.0	165	1.0	155	0.5	153	0.5	P & EE(S) (19)
GPMG 7.62 mm	B	151	0.5	170	1.0	159	1.0	155	0.5	P & EE(S) (19)
Shotgun 12 Gauge	M	155	5	–	–	–	–	–	–	ISVR (23)
Pistol 0.38 inch	M	157	5	–	–	–	–	–	–	ISVR (23)
Rifle 0.22 inch	M	138	2.5	–	–	132	2.5	–	–	ISVR (23, 24)

Note * B = Blast Gauge
M = Microphone

39. The need to evaluate the means of measuring impulsive noise has already been taken up at APRE under Project P528. Among the instruments it is intended to study are improved impulse sound level meters, which may provide a simple means of monitoring impulsive noise. It was anticipated that the Dawe 1412A meter used in the early part of this study would be suitable for this purpose, but it proved to be inconsistent, particularly above 170dB, although it must be admitted that it was not originally designed for use in these circumstances.

40. The peak pressure level generated by Mortars varied considerably when either microphones or blast gauges were used. Hence, it is concluded that the Mortars themselves were the source of variation. Since it was not possible to forecast the peak pressure level for particular bombs, the maximum pressure level was used to determine the permissible number of rounds (1).

41. The recent measurements for the 30mm Rarden Cannon on FOX were not available for inclusion on the survey (1), but, on the same basis as used then, the Commander (with head in) and the Instructor should be adequately protected by Sonex ear plugs up to 1000 rounds per day. The position 20ft to either side of the gun muzzle, however, should be limited to about 60 rounds per day for men wearing Sonex plugs. This will be particularly important should FOX vehicles, or other vehicles using the cannon, be grouped close together on firing points.

Sensitivity to Impulsive Noise (see paras 25 and following)

42. Of the 155 men tested 27% were withdrawn after twenty rounds of SLR (Grade I), another 25% after 60 or 120 rounds (Grade II and III) and the remainder (Grade IV) were given no further test after exposure to 120 rounds. These Grade IV men may be regarded as relatively insensitive, although no one should be regarded as totally insensitive. The detailed figures are given in Table XI.

TABLE XI

RELATIVE SENSITIVITY OF 155 MEN EXPOSED WITHOUT PROTECTION TO SLR

Sensitivity Grade	I	II	III	IV	TOTAL
Rounds Fired to produce response	20	60	120	-	-
Number	42	26	13	74	155
Percentage	27%	17%	8%	48%	100%

43. The greatest amount of TTS occurred at 6,000 Hz in the majority of those men who responded to the rifle test. This result accords well with that found by Murray and Reid (2, 3).

44. There were seven men among the 155 who showed TTS greater than 50dB and up to 65dB (see Table XII). One of these was anticipated by two 15dB changes after preceding exposure, and three by single 15dB changes. It was for this reason that the criterion for withdrawal was modified to include a double TTS of 15dB as a partial safeguard. The other large TTS observed were precipitate, and in no way indicated in previous audiograms.

TABLE XII

UNPROTECTED MEN SHOWING LARGE TTS_2 AFTER FIRING 20 ROUNDS OF SLR (see text)

TTS_2	POST EXPOSURE HEARING LEVEL	FREQUENCY kHz	EAR	SENSITIVITY GRADE
60	65	6	Less exposed	II
65	60	8	More exposed	I
50	50	6	" "	II
55	70	8	" "	I
55	55	6 and 8	" "	II
55	55	8	" "	I
50	45	4	" "	I

45. The mean TTS was calculated for the immediate results after 20 rounds of rifle fire for all men and for the sensitive group (Grade I), and are given in Table XIII. The mean TTS for all men was remarkably low, but includes the sensitive group with a mean TTS of 15dB, and the isolated large TTS discussed above. Mean TTS was therefore regarded as an unreliable means of determining safe limits.

TABLE XIII

MEAN TTS_2 AFTER UNPROTECTED EXPOSURE TO 20 ROUNDS OF SLR

Group	Ear	Frequency kHz 3	4	6	8
All men (N=151)	more exposed	2.1	3.1	4.8	4.5
	less exposed	1.4	1.8	2.0	2.5
Sensitivity Grade I (N=41)	more exposed	6.5	9.7	14.9	13.4
	less exposed	3.1	5.5	5.8	8.9

46. Twelve men were exposed at successively closer positions and higher pressures generated by an infantry support weapon (Table XIV). Eleven were withdrawn on the same criterion as used for the rifle grading, and it was thought unwise to take the last man in closer than 185 dB (5 psi). Half of this small group of men had responded to 171 dB or 174 dB, and on this basis the men were divided into two equal groups. The rifle gradings of sensitivity within the two smaller groups were compared after amalgamating Grades I, II and III since, on this basis, roughly equal numbers of sensitive and relatively insensitive men would be expected. When these groupings are compared, the results from the different weapons and in the assessment of sensitivity, agree in eight cases out of twelve, but this was not statistically significant.

TABLE XIV

SENSITIVITY OF 12 UNPROTECTED MEN TO PEAK PRESSURE EXPERIENCED TO ONE SIDE OF AN INFANTRY SUPPORT WEAPON (SEE TABLE I)

Peak Pressure Level dB	Number Responding	Cumulative Response	
		Total	Percentage
165	0	0	0
171	2	2	17
174	4	6	50
177	3	9	75
180	2	11	92
183	0	11	92
185	0	11	92

TABLE XV

SENSITIVITY OF 12 UNPROTECTED MEN TO THE PEAK PRESSURE GENERATED BY AN HE CHARGE (SEE TABLE I)

Maximum TTS(dB)	Number	Percentage
20	1	8
15	2	17
10	5	42
5 or less	4	33

47. Except for one man, who was replaced, the same group of men as those exposed to the infantry support weapon were also exposed to an HE Charge. The amount of TTS produced in no case exceeded 20 dB. However, these were very experienced subjects and it is possible that, in this particular test, a TTS of 10 dB can be taken as a valid change. The number and percentage of the men showing maximum TTS at four levels is shown in Table XV. Two thirds of the men showed TTS of 10 dB or more, and when this grouping was compared with the rifle grading, only three of the twelve men were not classified similarly by each test, but, again, this is not statistically significant.

48. Half the large group of men who were tested with the rifle can be regarded as sensitive (Rifle Grades I, II and III), and half relatively insensitive (Rifle Grade IV). The small groups exposed without ear protection to the other noise sources were divided as nearly as possible into two equal groups. These were, for the support weapon, those withdrawn at 171 and 174 dB and those withdrawn at higher pressures. The small group exposed to HE Charge were divided on the basis of those who showed a TTS of 10 dB or more and those who showed less or none at all. Of the eleven subjects exposed to all three sources, and thus available for a three-way classification, four men were sensitive by all three tests, two more men were classified in the relatively insensitive group by all three tests, and the remaining five were in mixed categories (see Table XVI). We may therefore state that these exposures classified six men consistently and five men inconsistently. Using the binomial distribution, as few as five inconsistent results would be expected by chance in only 3.1% of such samples of eleven men. Therefore we may reject the null hypothesis that for these eleven men there was an equal chance for sensitive and insensitive responses to occur.

TABLE XVI

COMPARISON OF SENSITIVITY TO THREE IMPULSIVE NOISE SOURCES (11 MEN)

	Triple Responses in Agreement	Other Combinations	Total
Number of Categories	2	6	8
Observed Frequency	6	5*	11

*Probability that as few occur by chance 0.03

49. A general similarity may exist among the three sensitivity tests, but since the gradings have been telescoped it is not appropriate to say that any precise relationship exists, particularly as there was some flexibility in the choice of the dividing line between sensitive and insensitive categories. Indeed, if the various categories of sensitive response are considered separately, all sign of agreement

seems to disappear. It may be that the three tests are fairly effective in the identification of relatively insensitive men, but are not so within the sensitive group. On the other hand sensitive men may respond to a different extent when exposed to impulsive noises of different types. Much more work needs to be done in this area, before these points can be clarified.

50. The rifle test was repeated five times on eighteen subjects. Although the proportions of the grades do not change significantly (chi-square 2.52, Friedman), it is clear from the results given in Table XVII that the repeatability of this test was not good. This was also the experience of Hodge and others [25] when they studied repeated exposure. This lack of repeatability or reliability of the response of any one particular man may account for the apparent lack of any consistency in the assessment of sensitivity to impulsive noise based on the three sources discussed above. However, for a group of eighteen or more men, the proportion of men in the four grades does not change to any great degree, although the men within the category may have changed places in some cases.

TABLE XVII

SENSITIVITY GRADINGS OF
18 MEN TESTED ON 5 OCCASIONS

Repeat	Sensitivity Grade			
	I	II	III	IV
1st Test	4	4	2	8
2nd Test	5	3	4	6
3rd Test	3	10	1	4
4th Test	6	4	1	7
5th Test	6	7	-	5

51. The subjects other than those given repeated rifle tests, were allocated to groups of 18 serially in the order in which they were received for testing. The distribution of sensitivity grades within these arbitrary groups is similar to that within the repeated classification, and none was significantly different from another (see Table XVIII). The minimum size of group necessary to ensure the inclusion of at least two men in the sensitive category (grade I) appears to be about 20 men.

TABLE XVIII

SENSITIVITY GRADINGS OF THE FIRST
126 MEN STUDIED ALLOCATED SEQUENTIALLY TO GROUPS OF 18

Group	Sensitivity Grade			
	I	II	III	IV
1st Group	4	3	0	11
2nd "	6	3	2	7
3rd "	4	4	0	10
4th "	3	2	4	9
5th "	6	3	2	7
6th "	4	2	2	10
7th "	6	4	1	7

The Effects of Weapons on Hearing

52. The provisional Damage Risk Criteria and Exposure Limits (DRC) for impulsive noise (5, 6, 7) assumed that the TTS_2 after one day's exposure (averaged over a large number of subjects) would be equivalent to the Permanent Threshold Shift (PTS) after 10 years of consistent exposure to the same noise. In monitoring the changes in hearing level occurring in this study, improvements in hearing or negative TTS were recorded. As noted in other studies (25, 26), these were occasionally quite large. Similarly there were occasional, unexpectedly high positive TTS, particularly among the repeated exposures to the rifle sensitivity test. Both extensive negative and positive TTS were regarded as part of the inherent variability of human response, and included with the majority of the data.

53. In the formulation of their DRC Coles et al (7) did not convert TTS obtained, over the time two to six minutes post-exposure, to a standard time of two minutes, mainly because a validated procedure was not available and their post exposure times were short. At that time there was available a conversion equation put forward by Ward et al (27), but this was for recovery from TTS produced by exposure to steady-state noise. Recently, Fletcher (28) has published some preliminary data upon recovery from TTS induced by impulsive noise. Although he concluded that the two recovery processes are different, equations fitted to his data for impulsive noise as far as one hour post-exposure yield similar curves for all the frequencies tested, and more importantly similar to the equation proposed by Ward for steady-state noise. Experience in collecting data from army training situations produced many delays beyond the short period of six minutes usually associated with audiometry but not more than 40 minutes, hence, the TTS data in the current study was all converted to TTS_2 by the following equation:

$$TTS_2 = TTS(t) + 8.4532 \log_{10}(t/2)$$

which was derived by a least square fit to Fletcher's data for the first hour of recovery.

54. The median, mean and variance of the converted TTS data was calculated for each group of men exposed to measured pressure levels. In most cases the samples were small, but relatively "normal". The proportion of the population with TTS less than 20 dB at 3, 4, 6 and 8 kHz was calculated using the normal variate (single tailed). The detailed information is given in Table XIX. Since the data is based on small samples the variance may be unnecessarily high, but it would appear that an acceptably high proportion of the population has been protected by the Sonex ear plug issued to soldiers.

55. The data obtained from protected personnel should not be extended to validate the provisional DRC. An attenuation of 20dB has been assumed for that protection, as had been suggested (7) pending actual measurement of the attenuation of ear defenders against impulsive noise.

CONCLUSIONS

56. The firing of most army weapons presents a hazard to the hearing of men whose ears are unprotected while they are using weapons, or working in the immediate vicinity of them.

57. The Sonex ear plugs provided for the soldier give adequate protection against normal amounts of firing from most current Army weapons. A greater level of protection is available in the form of ear muffs RAF Mk III or equivalent, and is required for:

(a) Sustained firing (200-400 rounds in three to four hours) with the 81mm Mortar, in either the ground or vehicle-mounted role; eg in endurance firing.

(b) The Instructor and Commander with head out of the turret for sustained daily shoots with the 120mm Chieftain (more than 60 rounds).

(c) The gun crew of the 105mm Pack Howitzer firing more than 50 rounds at Charge 5 or greater.

(d) Men exposed to the firing of more than five rounds consecutively from the 84mm Anti-Tank Gun Carl Gustav. Men protected by Sonex plugs and firing five rounds in two minutes should be rested for at least one hour before further exposure to noise of any kind.

58. The provisional criterion and exposure limit for impulsive noise, the correction factors for the number of rounds fired per day, and the assumed attenuation of ear defenders against impulsive noise all require further validation. Pending such validation an approximate, but worthwhile assessment of the risk to hearing from impulsive noise is provided by these provisional exposure limits.

59. Further information on the relation between impulsive noise exposure and permanent hearing loss is unlikely to be derived easily from the monitoring of soldier's hearing during the intense, but variable, exposures available within the Army Training Programme; see paragraph 63 below.

TABLE XIX

SUMMARY OF EFFECT OF WEAPON (other than SLR) NOISE ON HEARING

Weapon	Men	No	Position	No. of Rounds	Protection	Assessment % Protected
Chieftain	General Crew	8	Variable	Av 90	Sonex	84%
Chieftain	Instructor	6	Rear of Turret	70-90	Sonex	95%
Centurion	Instructor	9	Rear of Turret	190-320 (Av 287)	Sonex	93%
Centurion	Instructor	9	Rear of Turret	50-108 (Av 81)	Sonex	96%
Centurion	Crew	19	Variable	180-216 (Av 197)	Sonex	73%
Gun Howitzer 105 mm (Charge 5-7)	Crew	12	Variable	16-50 (Av 47)	Sonex	89%
Mortar 81 mm on FV 432 (Ch. Super and 5)	Crew	17	Layer and Loader	16-48 (Av 35)	Sonex	99%
Wombat 120 mm on FV 432	Crew	7	No 1 and No 2	5-10 (Av 8)	Sonex	94%
Gun 84 mm Carl Gustav	Crew	8	Gunner	5	Sonex	93%
Gun 84 mm Carl Gustav	Crew	8	Loader	5	Sonex	89%
Gun 84 mm Carl Gustav	APRE Subjects	12	32 ft to one side	1	NIL	87%

60. In particular, exposure of unprotected ears to the long duration pulses, eg those associated with firings of heavy rocket systems, will probably exceed the provisional limits, even for a single round; further work on the hazard to hearing from rocket noise would appear necessary.

61. The range of sensitivity to impulsive noise as measured by the production of temporary threshold shifts varies very widely among men. Repeated tests show that the sensitivity is not stable, but varies from one occasion to another. Hence it is important to determine the group response for a large sample of men, in order to assess the effects of a given weapon.

RECOMMENDATIONS

62. An evaluation should be conducted of instrumentation used in the measurement of impulsive noise in terms of peak transient pressure and pulse duration, or some agreed equivalent. Simplicity of operation and instruction of staff in its use are considered important and second only to the accuracy achieved.

63. Precise validation of the criterion and exposure limits for impulsive noise should be pursued by careful monitoring of human volunteers in controlled laboratory experiments. A device is needed which is capable of reproducing peak transient pressures from 130dB to 160dB or greater, coupled with pulse durations of 0.5 to 1000 milliseconds with variable but controlled rates of fire up to those experienced with machine guns, and a total exposure of 1000 rounds.

64. A method for measuring the attenuation of hearing protectors against impulsive noise is needed and should be developed in support of the proposed use of the provisional exposure limits to impulsive noise.

65. The suggestions for hearing conservation discussed in the Appendix to this report should be considered for use or extension of use within the programme of hearing conservation for the Army.

66. The effect of small hearing losses on military efficiency has not been explicitly considered in this Report. Nevertheless it is quite obvious that hearing decrement, either temporary or permanent, will have an adverse effect on military performance. Most evidence on this topic has been anecdotal, and while this is valuable as far as it goes, it may be considered that studies under controlled conditions might be useful.

ACKNOWLEDGEMENTS

In any study of this nature, involving assistance from several different establishments, and diverse methods of measurement, it is difficult to list all the sources of help and encouragement. However, particular thanks are due to the individuals and establishments who provided pressure measurements, to the many Service units who co-operated in the measurement of human response, and especially to the gallant subjects who remained cheerful under the most trying conditions.

Thanks are also due to Anthea Abbott who took on a major part of the experimental programme, and to Mr M R Forrest for editorial assistance.

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Hearing Conservation

During the conduct of this project several precautions which may be useful in a hearing conservation programme for the Army, have been suggested or become self evident. They are listed here for consideration, and adoption where appropriate:

a. Intake Audiometry, particularly when it is known that a recruit has had previous noise exposure eg quarrying or game shooting.

b. Regular monitoring audiometry for personnel consistently exposed to intense noise eg range staff and gunnery instructors.

c. The issue of suitable and correctly fitted hearing protection to personnel necessarily exposed to intense noise.

d. The reduction of impulsive noise at sources whenever possible in the design of new weapons.

e. The issue of mandatory instructions regarding the use of hearing protectors during training, practice or accuracy checks, whether these be under peace or wartime conditions.

f. The inclusion in range standing orders of instructions regarding appropriate "ear defenders" for personnel using that range with specific weapons, and an instruction that all personnel entering the range should be checked for possession of that hearing protection at the entrance to the range by the Officer or NCO in charge, who should report deficiencies.

g. Officers and NCOs in charge of ranges and those in charge of men using range facilities should have available a supply of Glass Down for unexpected or emergency use eg gunnery demonstrations to visiting military staff or civilian representatives.

Most of the above provisions are of course covered by DCI 19/66 [29]. It is, however, obvious that hearing protection in the Army is not popular and the terms of this DCI are not consistently enforced. Some units are in fact conscientious in their use of hearing protection; on the other hand, abuse of soldier's hearing has been seen during the course of this and similar studies on so many occasions that it would be unfair to single out individual offenders. Despite the unsatisfactory state of the civil law at present, abuse of just this type has resulted in heavy damages awarded against civilian employers[30]. Without doubt the hearing of the soldier is as valuable as that of a civilian, indeed it may well be more important to him on operations.

Intake and monitoring audiometry is not covered by DCI 19/66 [29]. Nevertheless it is felt that audiometry is a valuable safeguard for individual hearing, and serial audiometry especially important where regular exposure to intense noise exists, as with weapon instructors.

When the anticipated production of intense noise by weapons under development cannot be reduced by design to a level below the permissible exposure limits for the intended crewmen, the costs of hearing protection and, if necessary, communication aids, should be included in the cost of the new weapon development, when the necessary equipment is not already available in service.

The extent to which reduction of communication by passive hearing protection is of importance to an Army using Sonex ear plugs, should be studied in relation to unaided verbal communication and the use of various radio and other communication aids.

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Date of Search: 16 Apr 2009

Record Summary: WO 404/46
Title: Effects of noise on hearing. Part 1, weapon noise
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) REPORT 39/73
Held by The National Archives, Kew

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