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LABORATORY DEVELOPMENT OF AN AMPLITUDE-SENSITIVE EAR PLUG

by

M R Forrest

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SUMMARY

The theoretical basis for the attenuation given by various forms of ear defender is examined, particular attention being paid to those designed to attenuate selectively gunfire noise rather than speech. Details of a modification of the familiar V.51R ear plug are then given in which the change in the nature of the air flow through a small orifice, occuring at high pressure levels, is used to provide the selective attenuation. A series of laboratory experiments used to verify the theoretical predictions of the modified plug's performance are described and brief mention is also made of other relevant work. The likely applications of the plug are discussed.

CONTENTS

INTRODUCTION

1. Ear defenders to protect the user against unwanted noise are commonly a simple barrier between the noise source and the ear drums, which in the case of the ear plug fits into the entrance of the ear canal. One of the chief disadvantages of ear defenders is that in attenuating unwanted noise they also attenuate wanted sounds of which the most important is usually speech.[1]

2. Several attempts have been made to design ear defenders with a higher attenuation for certain types of noise than for speech; it is of course necessary that the noise differs from speech in some physical respect. The plugs described have been designed for military field-firing exercises in which live ammunition is used; good hearing of speech is essential for safety but lack of ear protection is likely to lead to noise-induced hearing losses.[2] If a plug, which is the most convenient form of defender for this purpose, gives an increased attenuation at very high noise levels the requirement is easily met, as gunfire noise reaches peak levels over 160dB s. p. l. but has a duration of only a few milliseconds. The mechanism for this is provided by the increase in the acoustic impedance of a small orifice at high pressures.[3,4,5] This phenomenon is well known and important in the design of resonant absorbers and mufflers for intense noise but does not appear to have been previously applied deliberately to the design of ear plugs.

Choice of Plug

3. The ear plug finally chosen was a normal Sonex plug with the core removed and replaced by a 0.005 inch shim disc pierced by a 0.025 inch diameter orifice; this modified Sonex is referred to here as the Institute of Naval Medicine (INM) amplitude-sensitive plug. The normal Sonex plug is one of several commercial versions of the well known V. 51R design and is widely used in the British armed forces; it was chosen as a basis for the INM plug partly because it was easily modified and readily available, but also because its properties were familiar and well understood. Both plugs are illustrated in Figure 1.

4. In order to check whether the INM plug really did offer any advantages over the conventional Sonex, an extensive series of tests had to be made on the noise-protection, speech-communication and other aspects of both plugs. The most important of these tests were carried out in the field,[6] often during normal training; but before this the properties of the plugs were examined in the laboratory so that the optimum configuration could be chosen and a clear insight obtained into their operation. It is with this laboratory investigation that the present report is concerned.

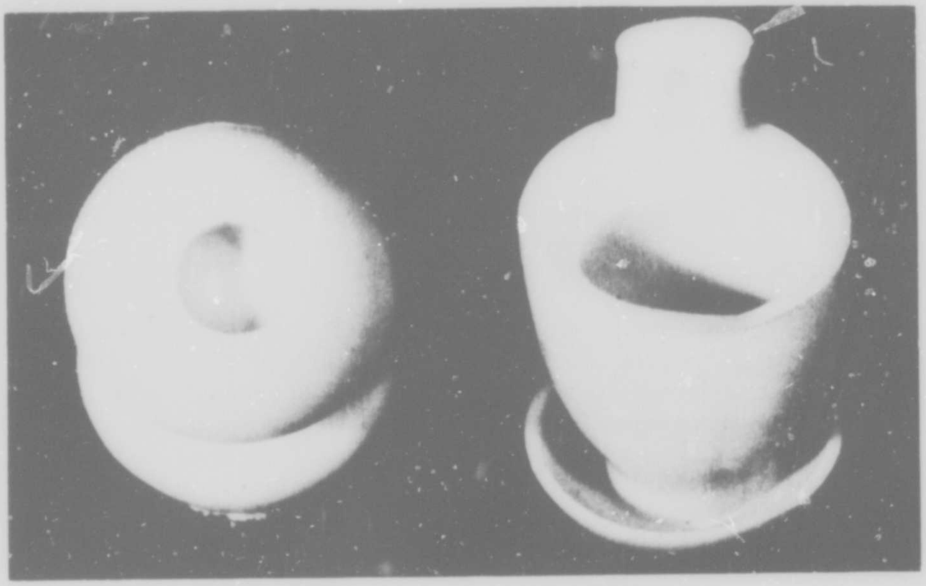


Fig. 1a Sonex ear plugs

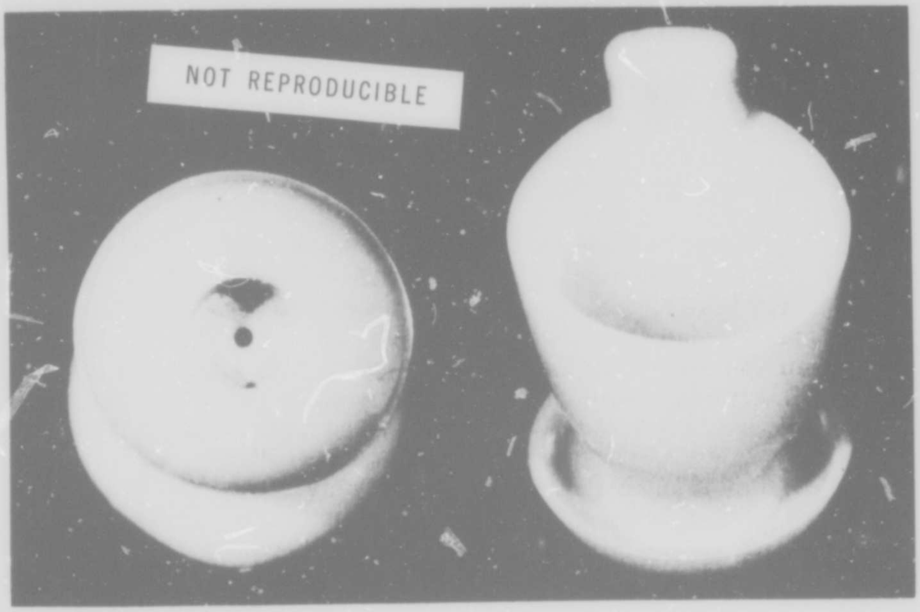


Fig. 1b INM - Modified ear plugs

Fig. 1 Sonex and INM ear plugs

Laboratory Investigations

5. The methods of investigation fell into three groups. The first was the measurement of the pure-tone and impulse attenuation in artificial-ear couplers, which gave rapid and precise results at the expense of some uncertainty about their application to real ears; this was used to determine the optimum configuration of the plug. In the second method the pure-tone and speech attenuations were measured necessarily at low level, using the threshold-shift techniques in real ears; to some extent these results were overshadowed by the later field trials but were important in showing whether field trials were justified and what form they should take. The third method of evaluating the INM plugs was the use of cadaver ears, which could be used with pure tones and impulses over a wide range of sound levels. As this method has been described in a separate report in this series,[7] details are not included here.

THEORY

Calculation of Attenuation

6. Any calculations of the attenuation given by an ear defender are necessarily approximate as many of the properties of both the defender and the ear are difficult to measure; moreover there is considerable variation between ears. Nevertheless such calculations are very useful in gaining an insight into the operation of a defender with a view to improved design and interpretation of experimental results. A good description of the problems involved is given by Von Gierke and Warren[8] and by Zwislocki[9], and hence only an outline description is given here.

7. For a normal 'solid' ear plug, that is, one without any internal air passages, the attenuation can be calculated in terms of its mass and dimensions, the stiffness of the meatus walls, and the impedance of the ear drum and the air in the meatus. Unfortunately the stiffness of the meatus walls is rather difficult to measure and may be expected to vary with the position of the ear plug; further, the structure of the meatus is complicated and sound transmission may occur through its tissues. Calculations of ear plug attenuation are therefore only useful where movement of the plug and the meatus walls is not the dominant mode of sound transmission, as is the case with the INM plugs and with several commercial types, at least over a limited frequency range.

8. Neglecting the movement of the body of the plug and the meatus walls, the INM and similar plugs may be represented as in Figure 2a. It may be easier to visualise this as an electrical network as in Figure 2b. To a reasonable approximation the eardrum impedance may be regarded as a resistance and a compliance in series, the air in the meatus as a compliance, and the acoustic element in the ear plug as a resistance and "inductance" in series; the electrical analogue for this is given in Figure 2c. This is, of course, a resonant circuit and the earplug/ear combination is a damped Helmholtz resonator. The attenuation is therefore zero at low frequencies, is negative at the resonant frequency providing the damping is not too great, and becomes large at higher frequencies.

9. The resistance, neglecting radiation resistance which is relatively small for orifices of this size, and "inductance" of small orifices in a thin plate are given by:-

$$R = \frac{1}{s}\rho \sqrt{2\omega\nu} \quad \frac{t'}{r}$$

and $$L = \rho \frac{t'}{s}$$

where ρ and ν are the density and kinematic viscosity of air, 1.2 kg m^{-3} and 1.5×10^{-5} m^2 sec^{-1} respectively. ω is the angular frequency of the sound, r is the radius of the orifice, s its area $= \pi r^2$, t' the thickness t of the plate together with an end correction approximately equal to 2r. For a 0.025 inch diameter orifice in 0.005 inch shim, $r = 3.2 \times 10^{-4}$ m and $t' = 7.7 \times 10^{-4}$ m, giving $L = 2.88 \times 10^3$ kg m^{-4} and $R = 3.9 \times 10^6$ kg m^{-4} sec^{-1} for $\omega = 2 \times 10^3$ sec^{-1}.

10. The compliance of the ear drum and the air in the meatus, neglecting the ear drum resistance, is approximately that of a volume V of air, that is $\frac{V}{\gamma P_o}$ where γ is the ratio of specific heats for air = 1.4 and P_o is atmospheric pressure = 10^5 N m^{-2}. This compliance, or capacitance, is therefore approximately 10^{-11} m^4 kg^{-1} sec^2 for $V = 1.4$ cm^3.

11. The ratio of the sound pressure inside the meatus to that outside is equal to

$$\frac{1}{C}\left(\frac{1}{jR\omega + 1/C - L\omega^2}\right)$$

and this function is traced out in Figure 3, for the quantities given. The sharpness of the resonance will be reduced in practice by the ear drum resistance which is neglected in the calculation, as are the sound transmission through the body of the plug and the meatal resonance at

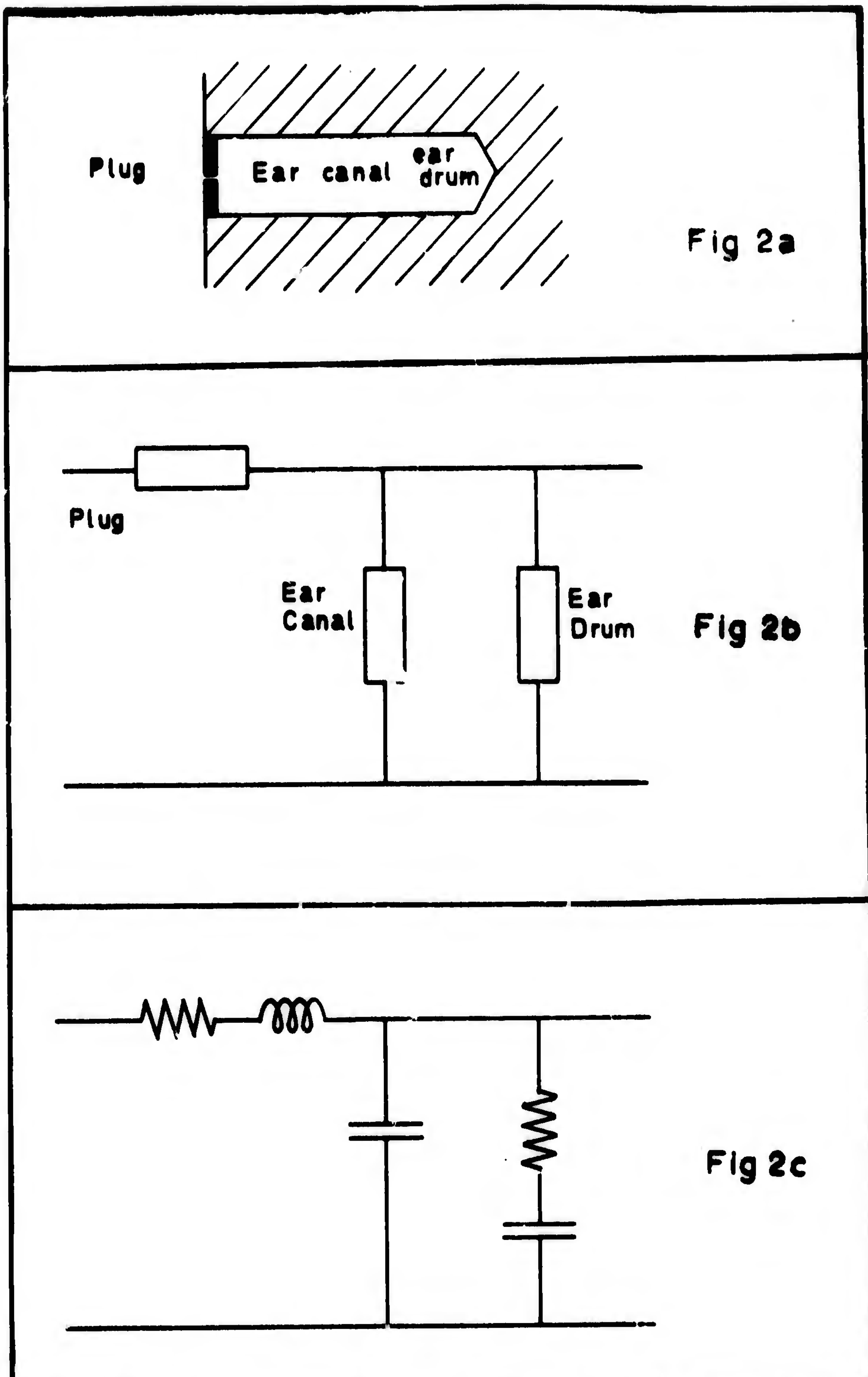


Fig. 2. Impedance of ear plug, ear canal and drum

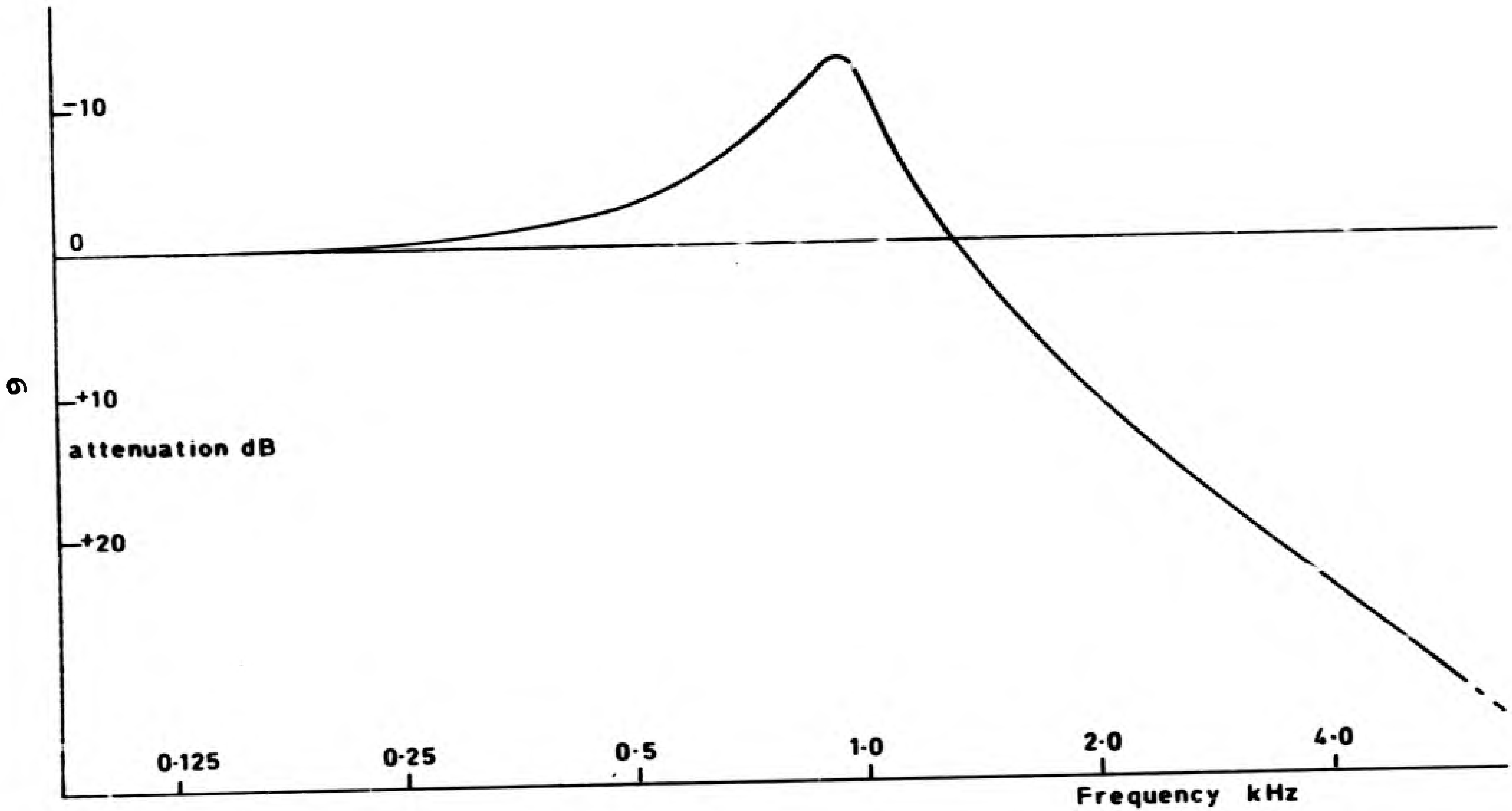


Fig 3 Theoretical attenuation of INM ear plug

higher frequencies. Nevertheless, in view of the approximations made, reasonable agreement is obtained with the experimental results.

12. The above argument holds only at relatively low sound pressure levels. When the displacement amplitude of the air in the orifice approaches t' the flow starts to break up and become turbulent; this will occur at pressures inside the canal of the order of 115dB s.p.l. The resistance is then increased by the addition of a turbulence component which, assuming that all the kinetic energy in the air flow is lost, is proportional to the particle velocity. i.e. $R_T = \rho \frac{u}{2s}$ where

u is the instantaneous particle velocity. R_T becomes the dominant component in the total resistance above about 120 dB s.p.l. In the case of gunfire noise where peak levels * above 160 dB s.p.l. are encountered, the total resistance of the orifice is very much greater than at lower levels.

Characteristics of the INM and similar Plugs

13. The characteristics of the INM and similar plugs can therefore be described as follows:- The attenuation at low level is strongly frequency dependent, there being a damped resonance around 1 kHz with an increasing attenuation thereafter. The attenuation above 2 kHz is quite large, as the unplugged ear canal has a strong resonance at about 3 kHz which is destroyed by insertion of the plug. The attenuation increases at high levels, first apparent for pure tone as a reduction of the gain at the resonant frequency. The reduction of high level short duration impulses of the type associated with gunfire approaches that of conventional ear plugs, and is dependent on the impulse level and duration. The non-linear part of the orifice impedance is of only small importance at the noise levels, generally below 130 dB s.p.l. encountered with industrial processes.

14. The linear part of the impedance, unlike the non-linear part, is dependent on the length of the orifice i.e. on the thickness of the shim, and a reduction in this thickness would therefore decrease the low-level attenuation; but as most of the effective length arises from the end correction, there should be no great advantage in using very thin shims. The 0.005 inch shim used seems a reasonable compromise.

* Where impulse noise levels are quoted they refer to zero-to-peak measurement.

METHOD AND RESULTS

Pure-Tone Attenuation in Artificial Ears

15. Artificial-ear couplers are very useful in the evaluation or development of some types of ear defenders as precise results are obtained easily and rapidly; but they suffer from two serious disadvantages when used with ear plugs. One is that agreed international standards for artificial ears refer mainly to their use in the calibration of earphones, and that artificial ears suitable for determination of ear plug attenuation are neither standardised nor commercially available. The other is that the attenuation of most types of ear plug depends critically on the properties of the tissues lining the external auditory meatus, as described in paragraph 7; to reproduce these adequately in an artificial ear would be extremely difficult.

16. The second difficulty entirely rules out the use of artificial ears for finding the attenuation of "solid" ear plugs: the restraint of the plug by the hard coupler walls produces a ridiculously high answer. If the plug is not "solid" but contains some form of acoustic element which reduces the attenuation (measured in a real ear), so that attenuation is chiefly a function of this element rather than of the meatus walls, then the results measured in an artificial ear will be meaningful and can be used in the evaluation or development of the plug. Comparison with published values for the attenuation of solid plugs with the artificial ear results should indicate whether transmission through the acoustic element in the plug or movement of the meatus walls is the dominant mechanism. For the INM plug and similar types, which give only modest attenuation at low and medium frequency, the artificial ear gives useful results at these frequencies.

Artificial Ears used in the Development of the INM Plug

17. The lack of standardisation for suitable artificial ears has led to a great variety of "one-off" designs; some of these are simply hard-walled cavities of the appropriate volume while others are impressively sophisticated.[10] Design of artificial ears is itself a facinating subject but will not be explored here.

18. Four different types of artificial ears were used in the development of the INM plug and the results from two are described:-

a. The simpler of the two artificial ears was a cylindrical cavity set in the centre of a 6-inch diameter aluminium plate. The diameter of the cavity was $\frac{1}{4}$ inch and length 1 inch. A $\frac{1}{4}$ inch (B & K 4136) microphone was placed at the far end with an O-ring to prevent leakage. Complete ear plugs were not used with this "ear"; instead a piece of steel shim pierced with the appropriate combination of orifices was placed across the entrance. This artificial ear could be used with both continuous and high-level impulse noise.

b. The other artificial ear was much more sophisticated and incorporated a simulation of the ear drum impedance measured on live ears,[11] although the "meatus" walls were still hard. The "meatus", which accepted complete medium-size ear plugs, was 0.8 inch (2 cm) long by 5/16 inch (0.8 cm) diameter; the ear drum impedance was a cavity of 0.8 cm^3 in series with an acoustic resistance, formed by an annular slit, of 400 cm^{-4} g. $sec.^{-1}$ ($4 \times 10^7 m^{-4}$ kg sec^{-1}). The sound at the "ear drum" was measured by a $\frac{1}{2}$ inch microphone (B & K 4134), and at the ear canal entrance by a 1 inch microphone (B & K 4132); the sound source was a hearing-aid telephone working into a closed volume. This artificial ear could only be used for pure tones.

19. Some of the frequency responses obtained with the first of these artificial ears are shown in Figure 4 for various shim thicknesses and configurations, and for the unobstructed "ear". The sound source in this case was a B & K artificial mouth which gave a constant sound pressure level of about 100 dB at the artificial ear entrance, over the frequency range of interest. The damped Helmholtz resonance between 500 Hz and 1000 Hz is evident, as is the effect of altering the shim thickness and the orifice diameter.

20. The frequency response of a complete INM plug in the second of the artificial ears is shown in Figure 5; also shown is that of the unobstructed "ear", which in this case is a fair approximation to that of a real ear,[12] up to about 4 kHz. The effective attenuation is of course the difference between these two responses. The plug response is shown at four levels from 100 to 130 dB s.p.l. (the highest sound pressure obtainable with the apparatus described) and the gradual increase in attenuation, first affecting the resonance, is easily seen; this is a useful indication of the greater increase to be expected at higher levels.

21. Several other ear plug configurations, including one with two shim plates separated by a short distance with an orifice in each, and another with multiple small orifices in a single shim plate, were tested in these and other artificial ears, but did not appear to have any advantage over the simpler configuration of one orifice in a single shim.

Impulse-Noise Attenuation in an Artificial Ear

22. This work was carried out using the simple artificial ear mentioned in the previous section. The sound source was a 0.22 inch/0.32 inch starting pistol; the sound pressure level at the "ear-canal" entrance varied according to the distance away from the pistol and the calibre of the blank cartridges used, and was measured with a $\frac{1}{4}$ inch B & K 4135 microphone. Unfortunately there was considerable variation in the

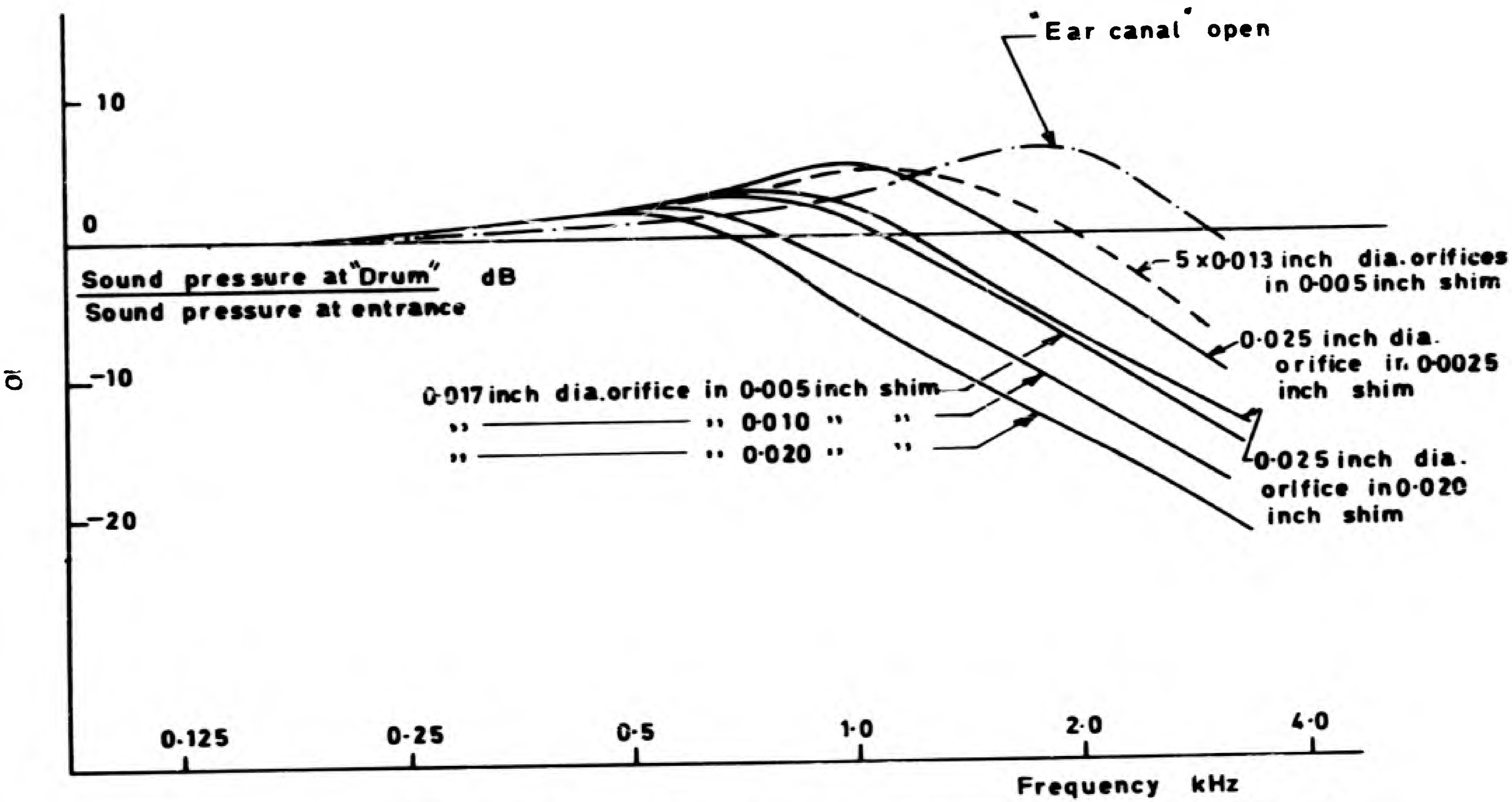


Fig 4. Pure tone attenuation of various orifice configurations in simple artificial ear

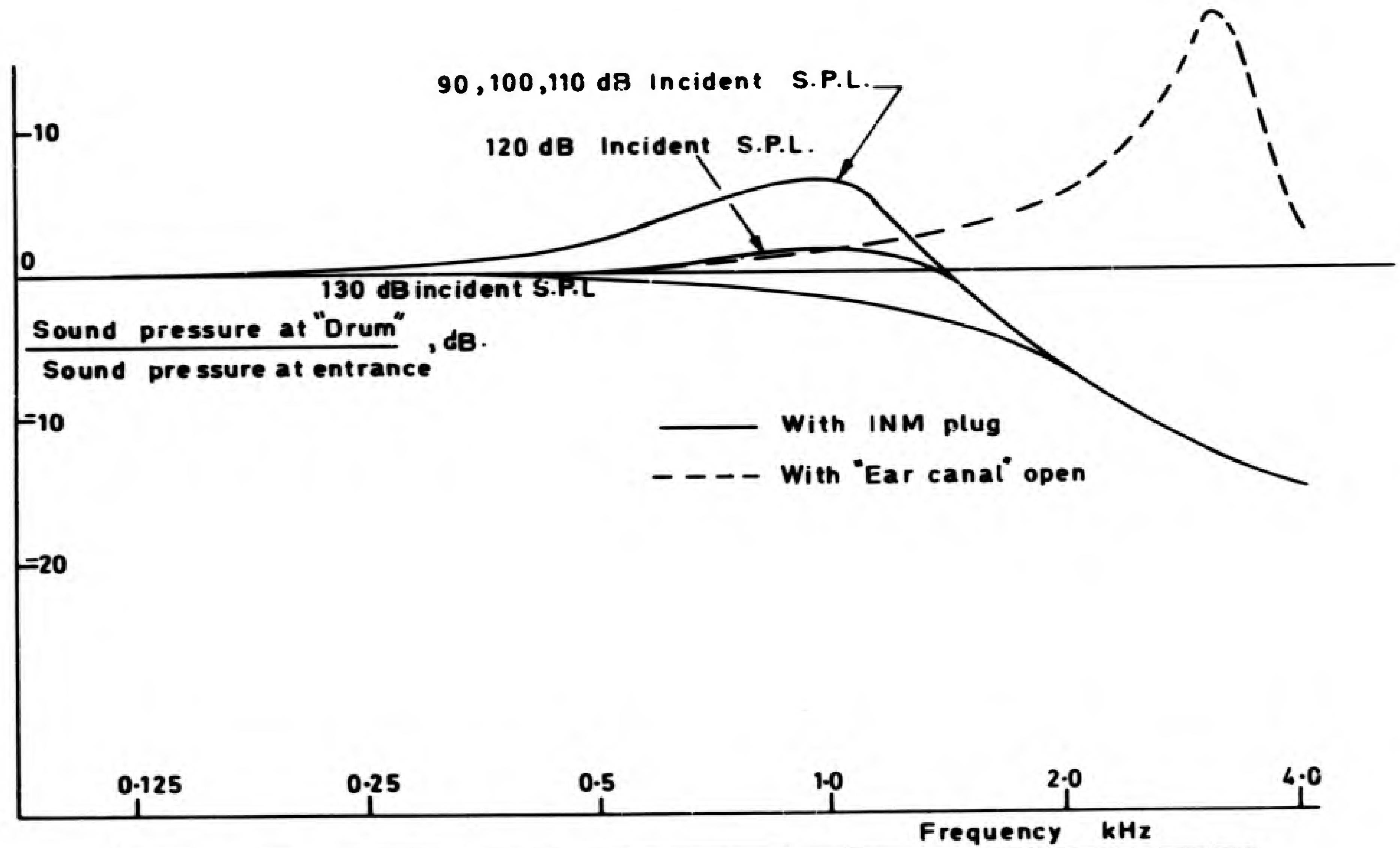


Fig 5. Pure tone attenuation at various sound pressure levels of INM plug, measured in an artificial ear.

noise from successive shots which is reflected in the experimental scatter. The output from the microphone was displayed on a storage oscilloscope screen and a photograph taken; a typical photograph and the definition of "peak level" is shown in Figure 6 and the method of calculating attenuation in Figure 7.

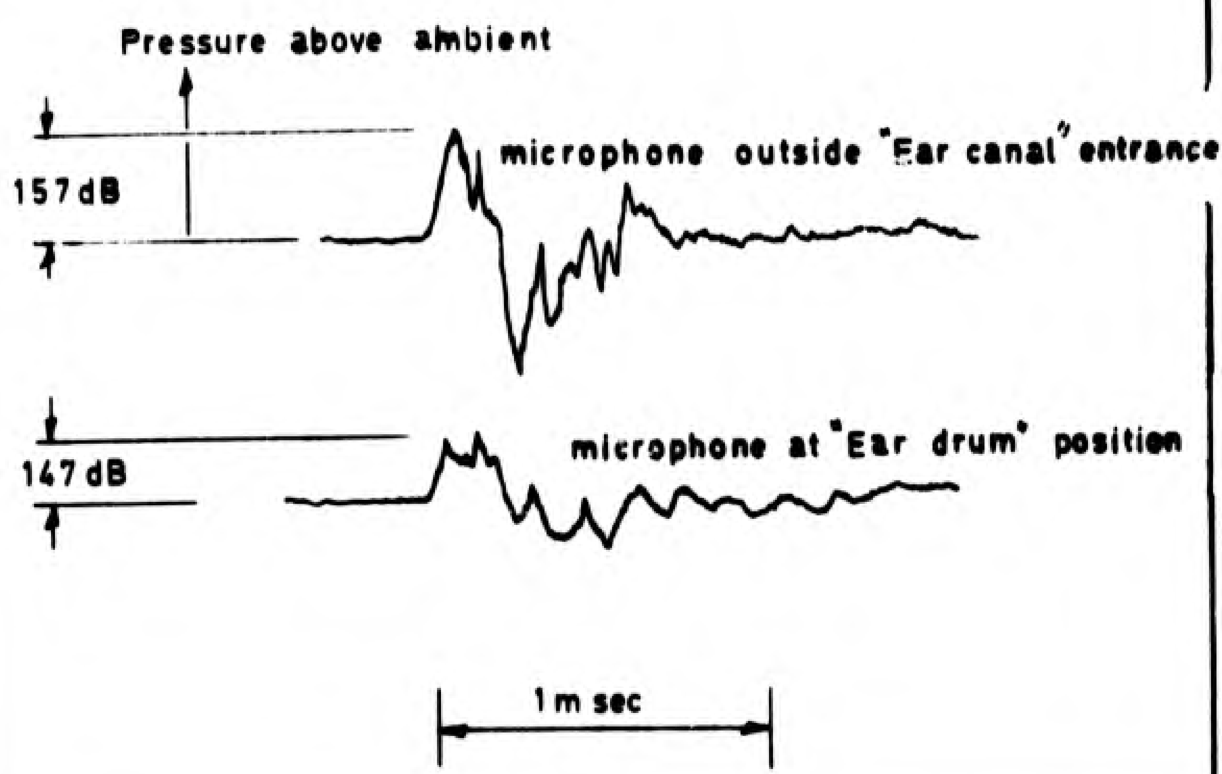
23. The sound pressure at the ear canal entrance was about 6 dB higher than it would be in a free field, when the ear canal was in line with the pistol; this pressure doubling, due to reflection, is also observed at the side of a real head. A similar increase is observed at the "drum" of the artificial ear when the "canal" was not obstructed, and again a parallel is observed with real ears; this of course affects the overall attenuation.

24. The impulse attenuation, for a 0.017 inch diameter orifice, is shown in Figure 8, and the increase in attenuation with incident impulse peak level is clearly seen. This increase is of the order of 1 dB per 2 dB increase in incident pressure, in accord with theory. Several other orifice configurations were tested and gave similar increases.

25. While the effect of the increasing impedance of the orifice is demonstrated quite well, it is difficult to say exactly how effective the attenuation will be. Apart from the difference between this very basic artificial ear and a real one, and the difference between the noise of a starting pistol and of a weapon, it is difficult to forecast exactly the effect on hearing of the change in the impulse shapes. For instance, the very sharp leading edge of the incident impulse is smoothed out on passage through the orifice; a slow rise time may well be less hazardous than a sharp one, but this is not certain. The only sure way to gauge the protection of any ear plug against impulse noise is to measure the temporary hearing losses produced in live subjects, as described in reference 6. Nevertheless it is encouraging to note that the impulse attenuation measured at the 160-170 dB levels commonly encountered with the self-loading rifle is of the order 15-20 dB when allowance is made for the pressure increase at the drum of the unobstructed ear, which is sufficient for most noises of this level. At higher levels a still higher attenuation is to be expected, limited ultimately to that of the Sonex plug.

Orifice Configuration

26. With the results with the artificial ears complete it was possible to decide which orifice configuration would be best for further work. It was decided that the simple 0.025 inch diameter



Sound source 0·22 inch blank

Ear canal entrance blocked by 0·005 inch shim with 0·025 inch diameter orifice

Peak pressure —decibels re 2×10^{-5} N/m^2

Fig. 6. Starting pistol impulse at entrance to artificial "Ear Canal" and at artificial "Ear Drum"

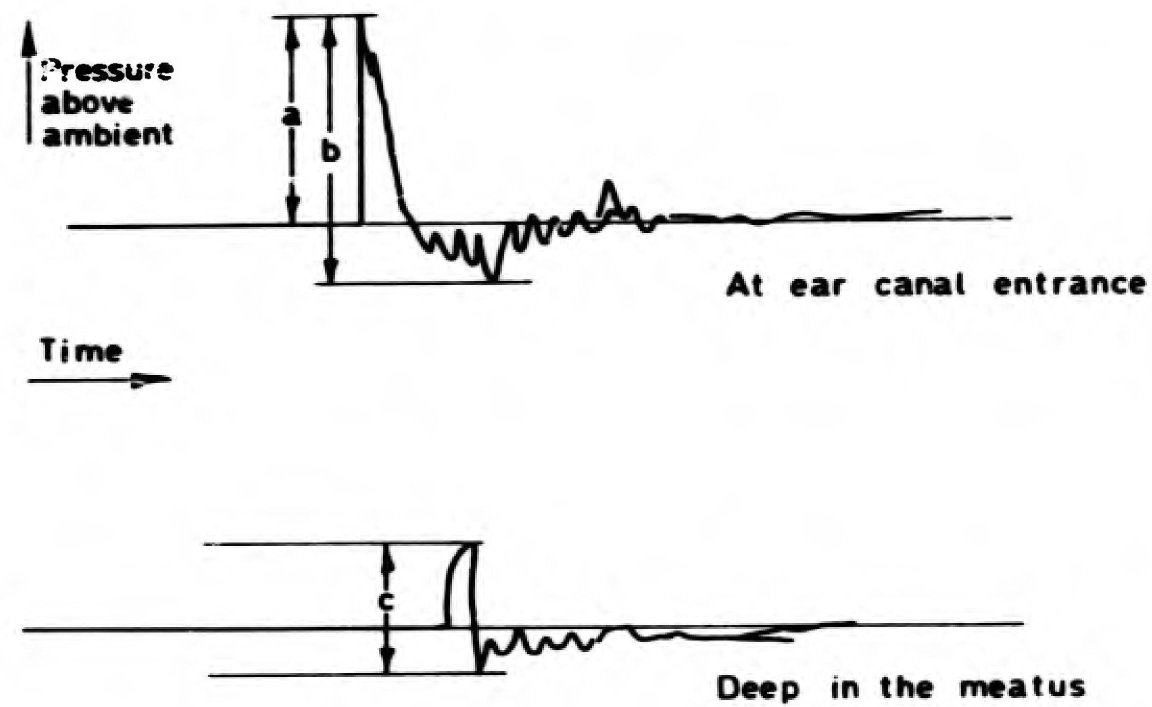


Fig. 7 Method of calculating impulse attenuation

Ratio of pressure excursions at ear canal entrance and deep in the meatus near the eardrum is calculated as 'b/c' for a peak pressure 'a' at the entrance.

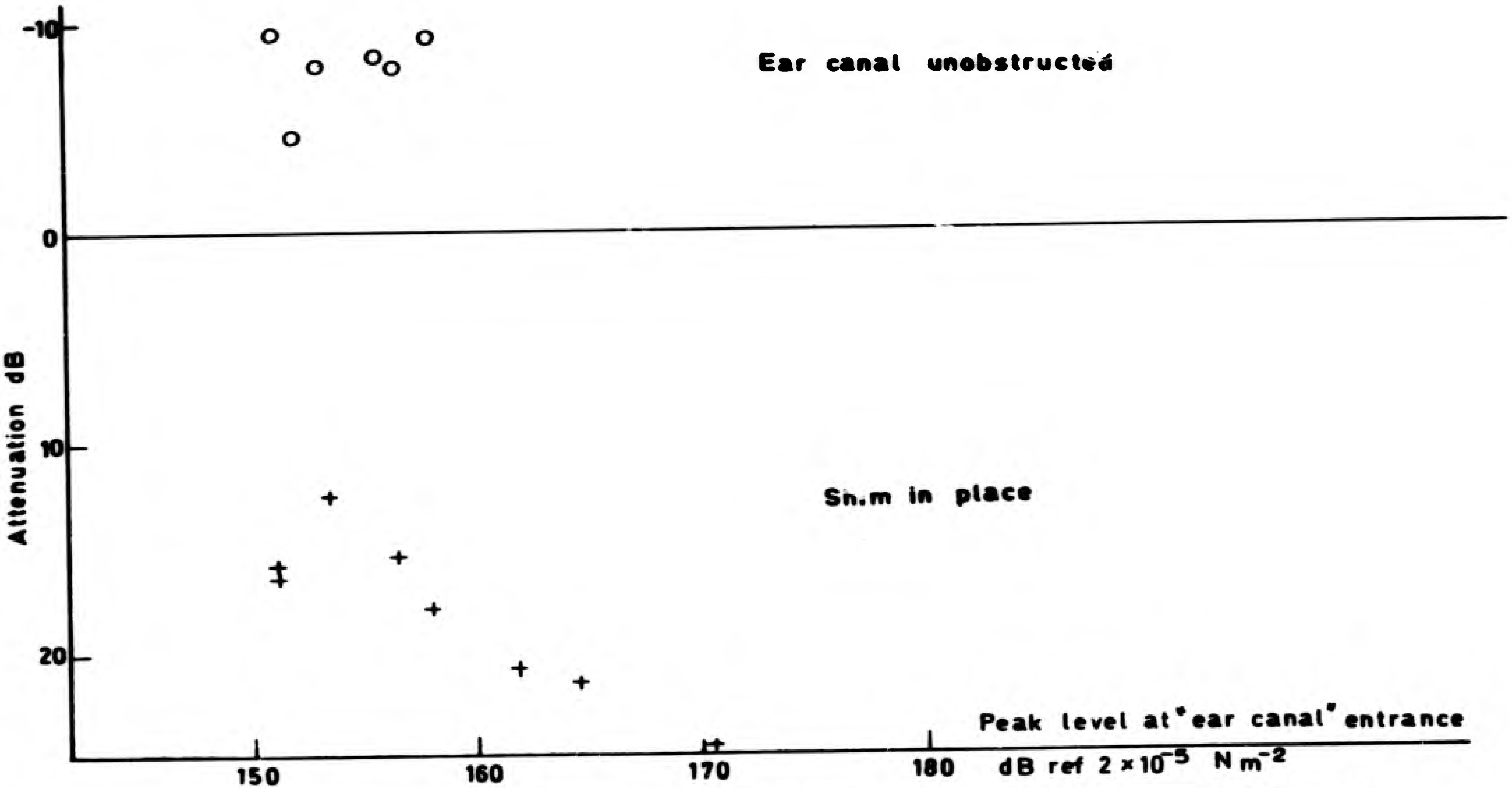


Fig.8. Impulse attenuation given by a 0·005 inch shim plate with a 0·017 inch diameter orifice, in a simple artificial ear.

aperture in 0.005 inch shim would probably give the best compromise between good attenuation of high level impulses and low attenuation of speech. The use of a single, large aperture also had the practical advantages that blockage by wax or debris was unlikely and cleaning would be simple, and also that the plug should be easy to manufacture.

Pure-Tone Attenuation by Threshold Shift Method

27. As a check on artificial-ear results the attenuation of the INM modified plugs was measured on real ears by the binaural free-field threshold shift method. This method is widely used and has been described in detail in the form of a U.S. Standard.[13] Strictly speaking a sound-insulated anechoic room is required together with a number of rather time-consuming precautions to eliminate, as far as possible, any bias or random error in the results. No anechoic room was to hand, and with the limited facilities available, it was evident that only an approximate answer would be possible. It should be remembered that the U.S. Standard procedure is intended as an accurate indication of the protection against noise given by an ear defender and the results are used as a final judgement on its efficiency against noise. With the INM modified plug the efficiency against noise is not related to the low level attenuation, and the results of the threshold shift are required only as a check on the artificial-ear results, and as an indication of the likely difficulty in communication that would be caused by the plug.

28. The measurements were conducted in an acoustic booth mounted in a sound-proofed mobile audiometric trailer. In order to reduce the standing waves in the booth as far as possible a warble tone was used instead of a pure tone. Attenuator steps were 5 dB. Six subjects were used; with three the threshold was obtained first with the plugs in position and with three first with the ears open. Results are shown in Figure 9.

Speech Attenuation by Threshold Shift Method

29. The speech attenuation of the INM plugs in quiet conditions was measured in freefield in the same acoustic booth as for the pure-tone attenuation. Fry's phonetically balanced monosyllabic word lists[15] played over a tape recorder were used as the signal. As before, a 5 dB step attenuator varied the signal level so that a speech intellegibilty curve (% score vs. signal level) could be obtained. The intersection of the speech curve with the 50% score level gave the speech reception threshold. Subjects repeated what they thought they heard over an intercom and this was later scored by the number of phonemes heard correctly. Subjects had no difficulty in obtaining 100% scores at suitably high signal level, with or without the ear plugs. Eight subjects took part

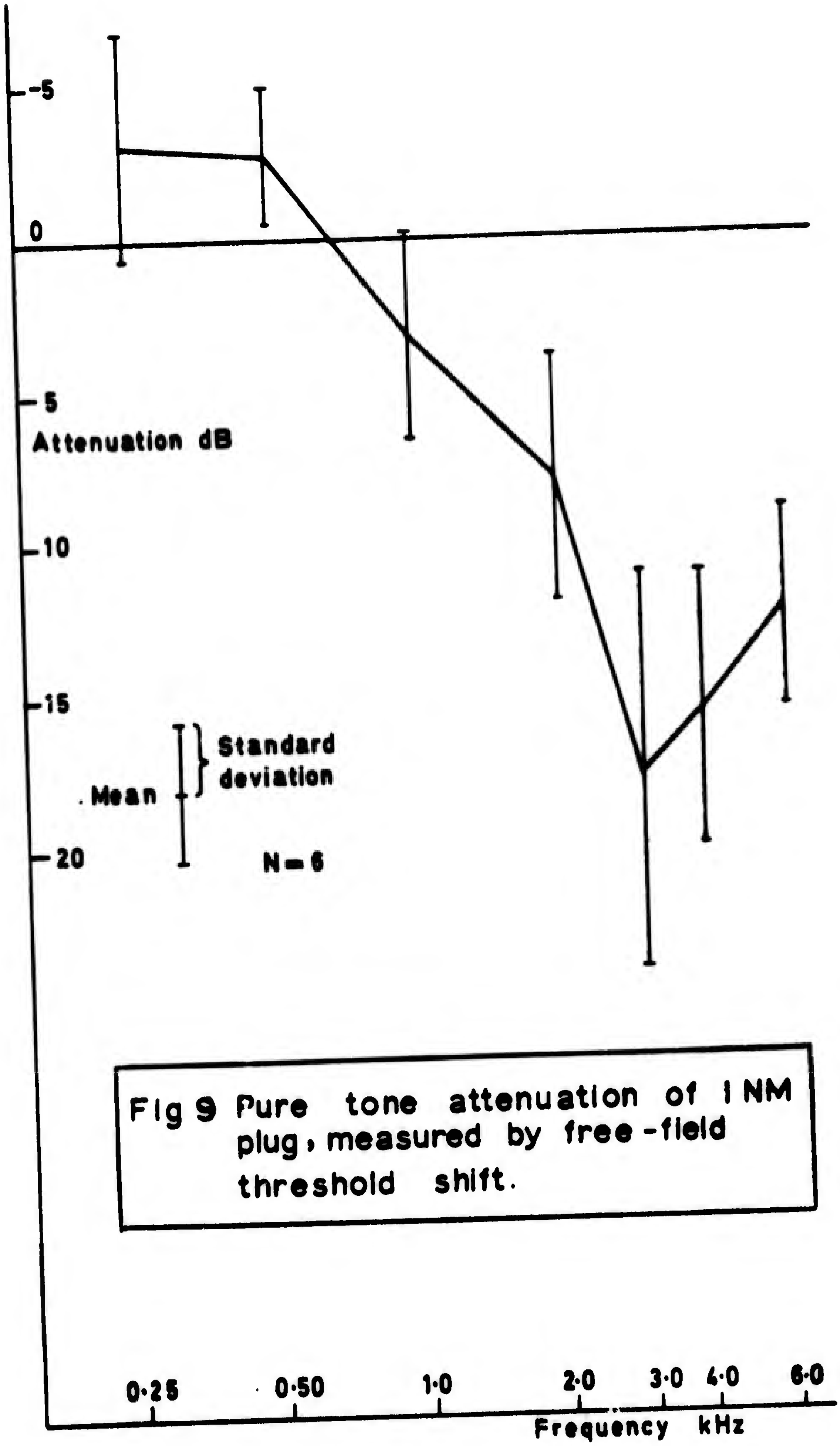


Fig 9 Pure tone attenuation of 1 NM plug, measured by free-field threshold shift.

in the experiment; with four the speech threshold was obtained first without plugs, and with the other four first with plugs. The mean speech attenuation was 5.25 dB with a standard deviation of 3.2 dB.

30. The speech attenuation in quiet is a good way of evaluating the likely effect on communication of an ear defender, but is unrealistic to the extent that in practice the environment is unlikely to be completely quiet nor is the speech necessarily near threshold intensity levels; moreover the subject, engaged in other tasks, may not be listening as intently as possible.

DISCUSSION

31. The amplitude-sensitive properties of the INM plug are likely to give a significant advantage for intermittent gunfire-noise applications, but it may be asked if other defenders with similar properties exist. In fact several such defenders do exist, among them the ERDEfender headset, the Selectone-K ear plug,[2,15] the Lee-Sonic "Ear Valv".

32. ERDEfender Headset. The ERDEfender headset, which uses electronic processing of the signal, works very efficiently but is too bulky, expensive and fragile for the present application.

33. "Ear Valv" Plug. The "Ear Valv" plug is much more compact, although still a little bulky by ear plug standards; it incorporates a flutter valve which is alleged to butt against and thereby seal an orifice when actuated by high sound pressures. The mechanism is very nicely designed and made, and the "valv" itself very light in weight but it seems unlikely, bearing in mind the very short durations of the pulses in gunfire noise, that the inertia of the "valv" would allow it to close in time to offer adequate protection. Nevertheless the "Ear Valv" does show some evidence of increased attenuation at very high sound pressures, but this can be attributed to the increased resistance in its internal air passages rather than the closure of the "valv".

34. Selectone-K Ear Plugs. The Selectone-K ear plug was designed to attenuate selectively the high frequencies thought to be especially damaging to the ear, and incorporates a two-stage acoustic filter giving a sharp increase in attenuation above 2kHz. It also shows an unclaimed increase in attenuation at high levels, again due to the increased resistance in its internal air passages. The same may be true of the Ruedi-Furrer ear muff[17] which, like the Selectone-K, was designed to attenuate high frequencies selectively.

35. Comparison of Speech Attenuation Qualities. The likely effect on communication of the plugs can be estimated from their speech attenuation. That of the Selectone-K has been given as 15 dB[2], and that of the Lee-Sonic "Ear Valv" can be calculated, using a formula given by Coles and Rice[1,2] with data from Piesse[15], as 14 dB, although this may be a slight over-estimate. Against this the measured speech attenuation of the INM plug is about 5 dB, and the calculated attenuation 7.6 dB, a much more worthwhile improvement over the 20 dB speech attenuation provided by Sonex plugs[2].

36. The INM plug has the additional virtue of being simple and therefore cheap to produce. Being a modification of a well-proven design, it should not be particularly uncomfortable or difficult to fit, although no ear plug is entirely satisfactory in these respects.

37. The final test of any ear defender must always be under actual conditions of use and this was to be the next stage in development, for which the laboratory results would be an invaluable background.

CONCLUSIONS

38. The properties of the INM plug as measured in the laboratory agree reasonably well with those predicted by theory. These properties are shown to include an attenuation for high-level impulse noise approaching that of the currently used Sonex V.51R-type plug, but with a very much smaller attenuation for speech. It appears that this plug will be much preferable to the Sonex and other conventional plugs where good speech attenuation and impulse-noise protection are both necessary, and field trials to confirm this have been carried out and reported.[6]

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