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Westerstede, 02.09.2015

Stellungnahme zur Vergleichbarkeit der Schutzwirkung von Schalldämpfern und Gehörschützern

Bei der Genehmigung von Schalldämpfern ist die Frage von herausgehobener Bedeutung, inwiefern die Schutzwirkung mit der von Gehörschützern vergleichbar ist.

Nach Nr. 8.1.6 der Allgemeinen Waffenverwaltungsvorschrift kann ein waffenrechtliches Bedürfnis zum Erwerb von Schalldämpfern nur in Ausnahmefällen in Betracht kommen. Dies wird regelmäßig so ausgelegt, dass nachgewiesen werden muss, dass ein Schalldämpfer nicht nur geeignet oder vorteilhaft, sondern aus rechtlichen und/oder tatsächlichen Gründen notwendig ist.

In der Vergangenheit wurden entsprechende Anträge regelmäßig abgelehnt, weil Gehörschützer einen vergleichbaren oder sogar besseren Schutz als Schalldämpfer bieten würden. Um die Diskussion zu versachlichen und eine objektive Güterabwägung möglich zu machen, sollen hier die Grenzen der Schutzwirkung von Gehörschützern und Schalldämpfern aufgezeigt und typische Missverständnisse aufgeklärt werden.

Die Messung und Bewertung von Lärm und dessen Reduzierung bei den immens hohen Schalldruckpegeln, wie sie beim Schießen auftreten, ist hochkomplex und sehr abhängig von vielen Umgebungsvariablen. Exakte Aussagen lassen sich daher immer nur für eine bestimmte Messkonstellation in einer festgelegten Situation machen. Immer wieder in Urteilsbegründungen zu lesende Aussagen, wie z. B. „Kapselgehörschutz schützt das Ohr bis 40 dB, Schalldämpfer nur bis 30 dB", können nicht korrekt sein. Hier wird hier ein Anspruch auf Allgemeingültigkeit erhoben, ist dem stets mit Vorsicht zu begegnen.

Die tatsächlich durch Gehörschützer erreichbare Dämmwirkung weicht oftmals erheblich von den auf der Verpackung angegebenen Werten ab. Der wesentliche Grund hierfür dürfte sein, dass die Lärmbelastung unter jagdlichen Bedingungen sich von den Laborbedingungen bei den Zulassungsverfahren deutlich unterscheidet.

Die Messverfahren zur Ermittlung der Dämmwerte bei Gehörschutz betrachten deren Wirkung bei einem reinfrequenten tiefen, mittleren und hohen Ton. Hierdurch werden dann Dämmwerte für hoch-, niedrig- und tieffrequenten Lärm gemessen. Hintergrund ist, dass jeder Gehörschutz unterschiedlich gut bei verschiedenen Lärmfrequenzen dämmt.

Unter echten jagdlichen Bedingungen werden diese Werte oftmals erheblich unterschritten. Zum einen stellt der Schusslärm ein chaotisches Lärmereignis, das nahezu das gesamte hörbare Frequenzband abdeckt (Abb. 1), die Belastung unterscheidet sich daher wesentlich von den Laborbedingungen. Zum anderen unterscheiden sich Kopfform (und damit die Passform der Gehörschützer) ebenso wie die Kopfbehaarung etc. in ihrer großen Vielfalt deutlich von dem standardisierten Kopfmodell aus dem Labor.

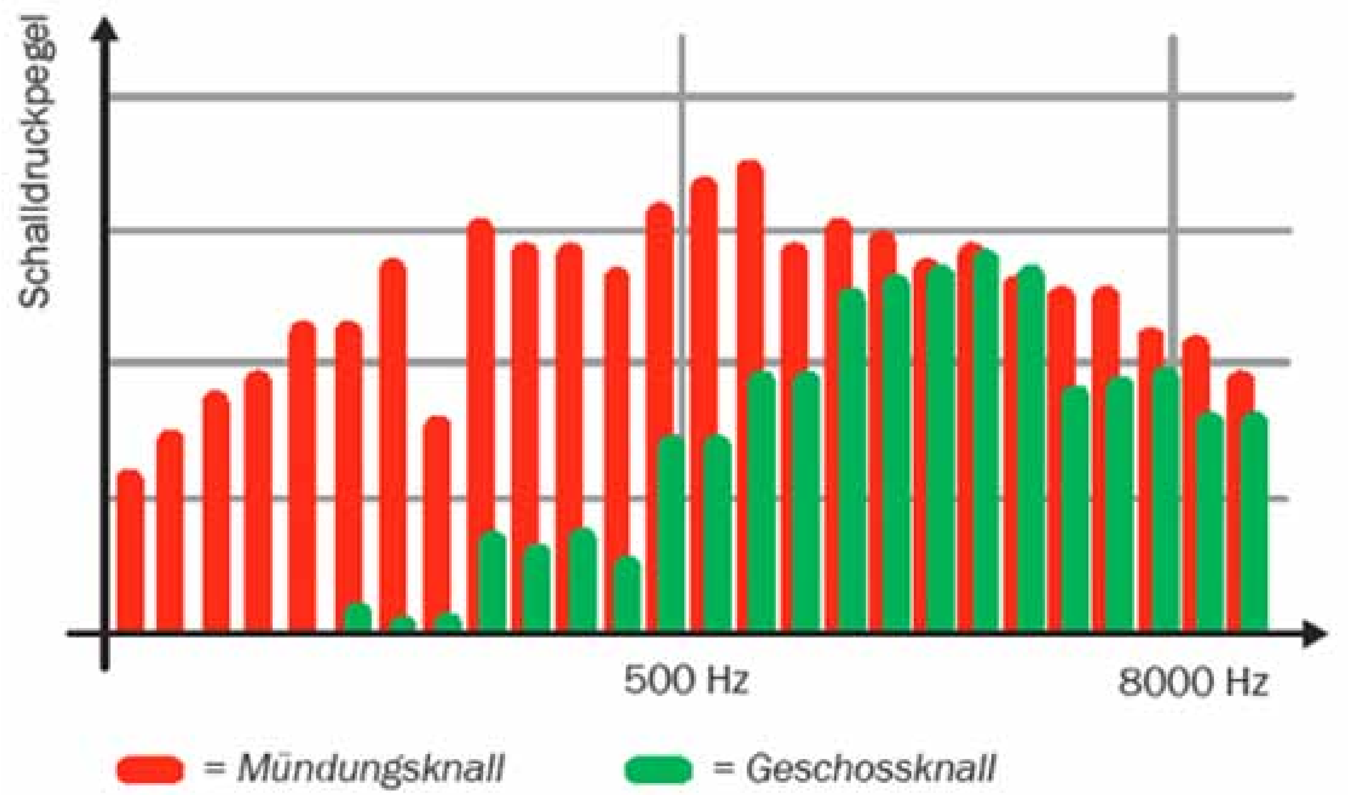

Abb. 1: Das Frequenzspektrum von Mündungs- und Geschossknall ist extrem breit und daher nur eingeschränkt mit den reinfrequenten Testtönen im Prüflabor zu vergleichen [aus 1].

Verschiedene seriöse wissenschaftliche Untersuchungen konnten dieses Problem aufzeigen. Schon 1996 zeigte eine Forschungsgruppe durch Auswertung der weltweit verfügbaren Daten aus Studien, dass die meisten Gehörschützer bei der Schussabgabe unter Feldbedingungen kaum die Hälfte der auf den Packungen angegebenen Dämmwerte erreichen konnten. Konkret erzielte Kapselgehörschutz durchschnittlich nur eine Schalldruckpegel-Reduktion von 11-17 Dezibel, während Gehörschutzstopfen nur Dämmwerte von 1-13 Dezibel aufwiesen [2].

Das Health and Safety Executive (Äquivalent der Berufsgenossenschaften in Großbritannien) untersuchte im Rahmen der Bewertung des Stellenwertes von Schalldämpfern für den Arbeitsschutz auch die tatsächlich durch Gehörschützer erzielbaren Dämmwerte [3]. Dabei wurde festgestellt, dass alleine mit Kapselgehörschutz durchschnittlich keine Reduktion des einwirkenden Lärmes unter die oberen Auslösewerte von 140 dB(C) der europäischen Arbeitsschutzvorgaben zu erreichen war (Abb. 2). Modernen Schalldämpfer-Modellen gelang dies dagegen mühelos (Abb. 3). Sie erreichten etwa 7 Dezibel mehr Schalldruckpegelreduktion am Ohr als die getesteten Gehörschützer und ließen somit weniger als die Hälfte des Schalldrucks wie bei Gehörschützern an das menschliche Ohr gelangen.

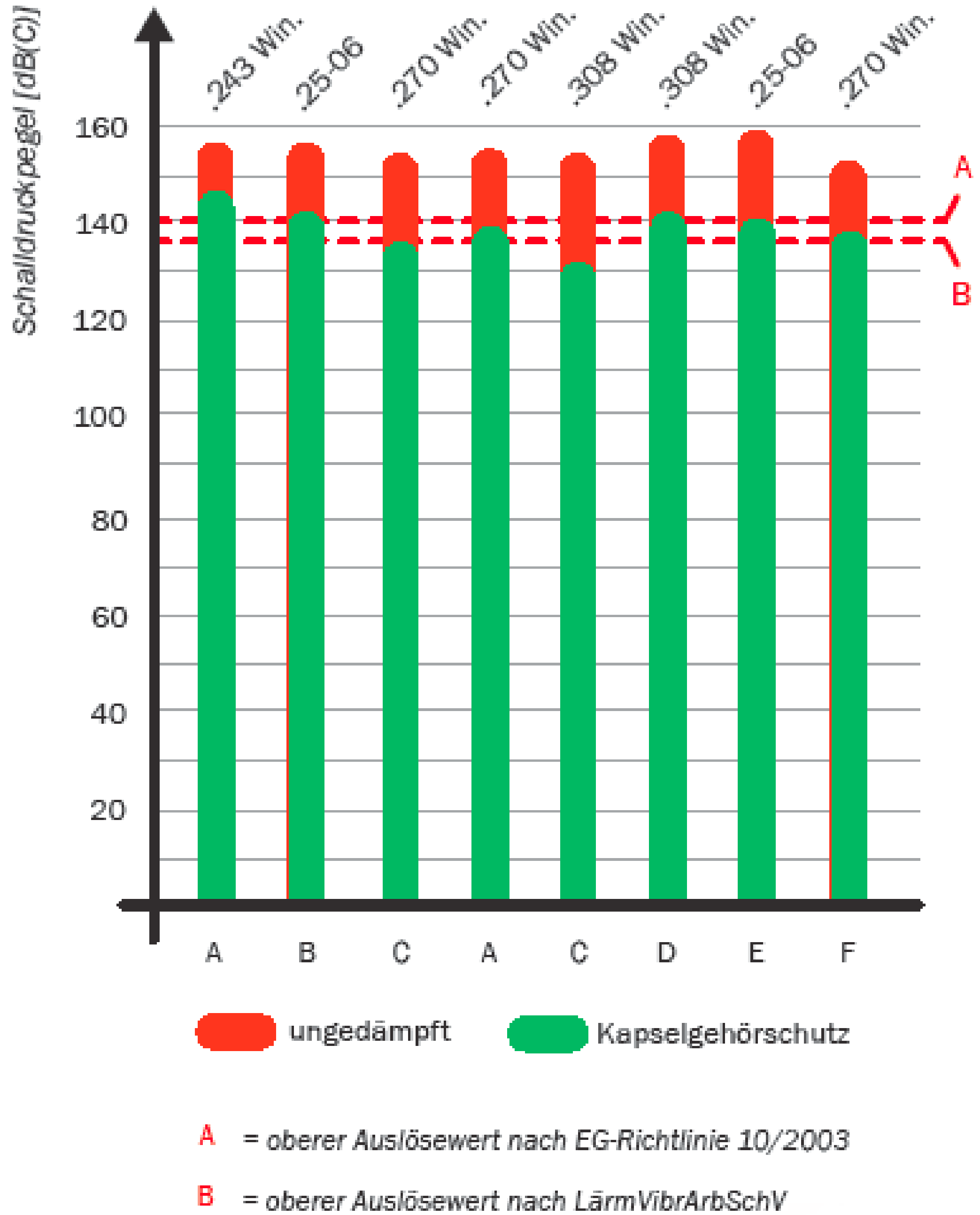

Abb. 2: Messung des Schalldruckpegels am Schützenohr mit Gehörschutz (grün) und ohne (rot) bei verschiedenen Kapselgehörschützern (Modelle A-F). Es ist deutlich zu sehen, dass durch den Einsatz von Kapselgehörschützern der obere Auslösewert der deutschen Lärm- und Vibrationsarbeitsschutz-verordnung von 137 Dezibel (C) in den meisten Fällen nicht unterschritten werden kann. Der bei allen getesteten Gehörschützer-Modellen durchschnittlich am Ohr anliegende Schalldruckpegel lag mit 140,1 Dezibel (C) sogar über dem großzügigeren EU-Grenzwert von 140 Dezibel (C) [aus 1].

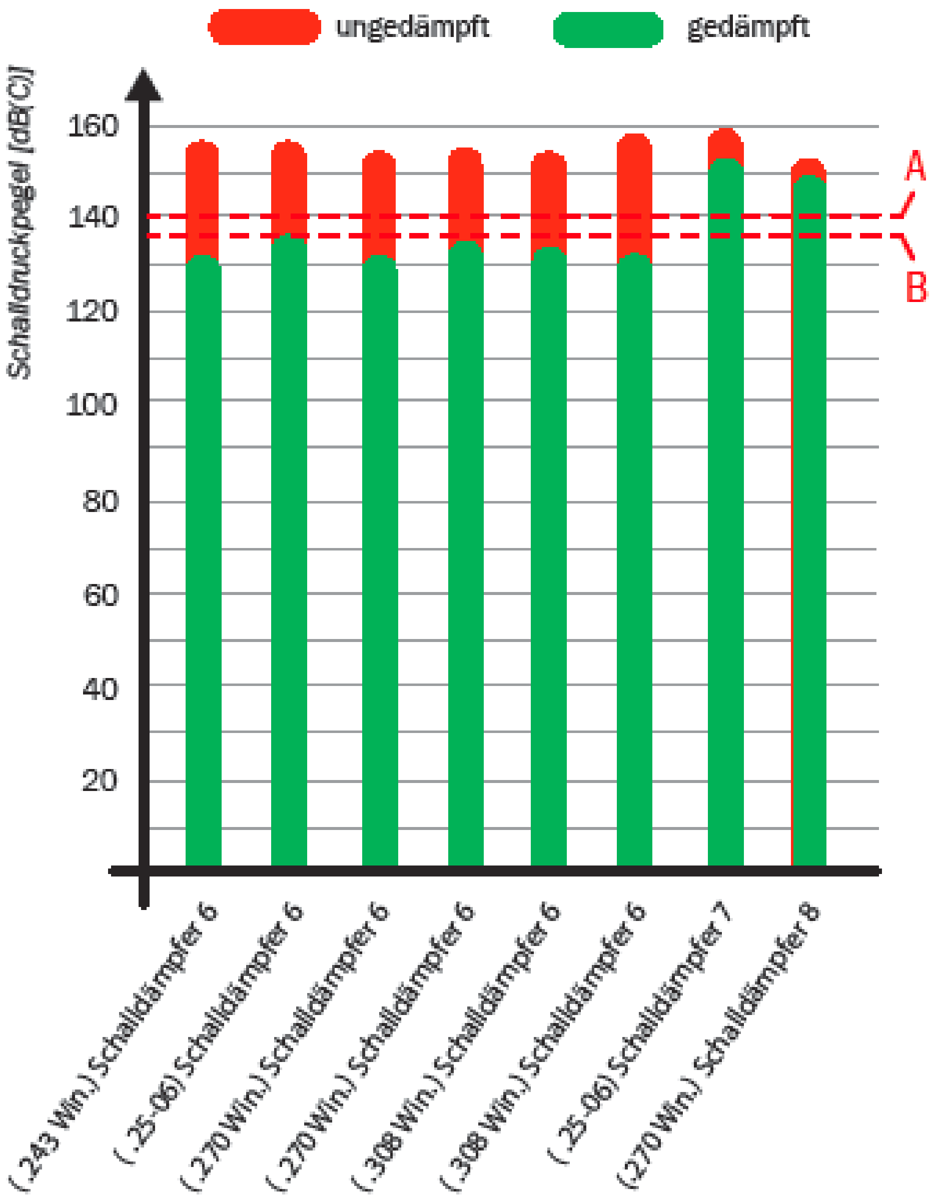

Abb. 3: Durch den Einsatz moderner Schalldämpfer (z. B. Schalldämpfer 6 in Verbindung mit verschiedenen Waffen) wird der obere Auslösewert von 137 Dezibel (C) sicher unterschritten [aus 1].

Aufgrund dieser Messungen wurde im Vereinigten Königreich festgestellt, dass unabhängig von der ohnehin in jedem Fall vorgeschriebenen Lärmdämpfung an der Quelle auch hinsichtlich der am Ohr anliegenden Schalldruckpegel nur durch Schalldämpfer die Vorgaben des Arbeitsschutzes erfüllt werden können. Nachfolgend wurden dort nicht nur für alle professionell Jagenden, sondern - trotz des sehr restriktiven Waffenrechts - für alle Jäger der Erwerb von Schalldämpfern auf Antrag freigegeben.

Auch eine aktuellere Messung aus dem Jahr 2011 bestätigt eindrücklich, dass die Minderung des auf das Ohr einwirkenden Lärms durch Dämpfer mehr als anderthalb mal so groß ist, wie durch Gehörschützer [3]. Der auf das Ohr einwirkende Lärm bei einer Waffe in .308 Winchester konnte durch den getesteten Schalldämpfer um 29,8 Dezibel auf 131,8 Dezibel vermindert werden (Abb. 4). Auch in dieser Studie konnte durch den Einsatz von Gehörschützern direkt am Ohr keine Reduktion des Schalldruckpegels auf unter 140 Dezibel (C) erreicht werden. Die getesteten Kapselgehörschützer erreichten bei der Messung unter Feldbedingungen nur Dämmwerte von 7-14 Dezibel (Abb. 5), die untersuchten Gehörschutzstopfen nur 1-11 Dezibel (Abb. 6). Diese Werte sind gut vereinbar mit denen der anderen zitierten Untersuchungen und müssen daher als valide betrachtet werden.

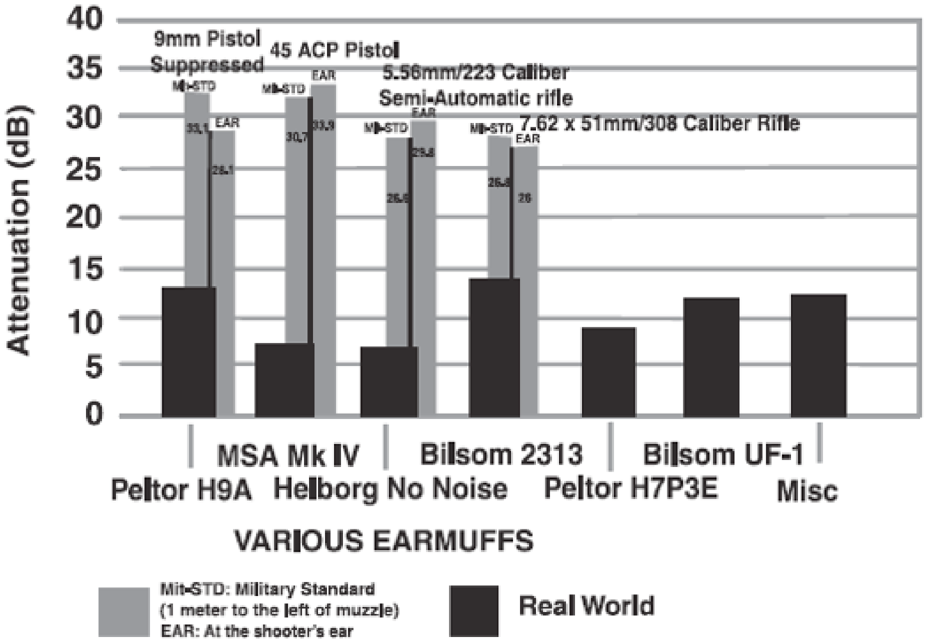

Abb. 4: Erzielbare Dämpfung durch Schalldämpfer 90° seitlich der Mündung in einem Meter Abstand (grauer Balken „MLT-STD“) und direkt am Schützenohr (grauer Balken „EAR“). Für eine Waffe in .308 Winchester zeigt sich dabei eine Lärmreduktion um über 30 Dezibel am Ohr. Im Vergleich dazu die unter realen Bedingungen erzielbare Dämmwirkung verschiedener marktverfügbarer Kapselgehörschützer [aus 4]. Die erheblich geringere Lärmminderung der Kapselgehörschützer im Vergleich zum Dämpfer ist offensichtlich.

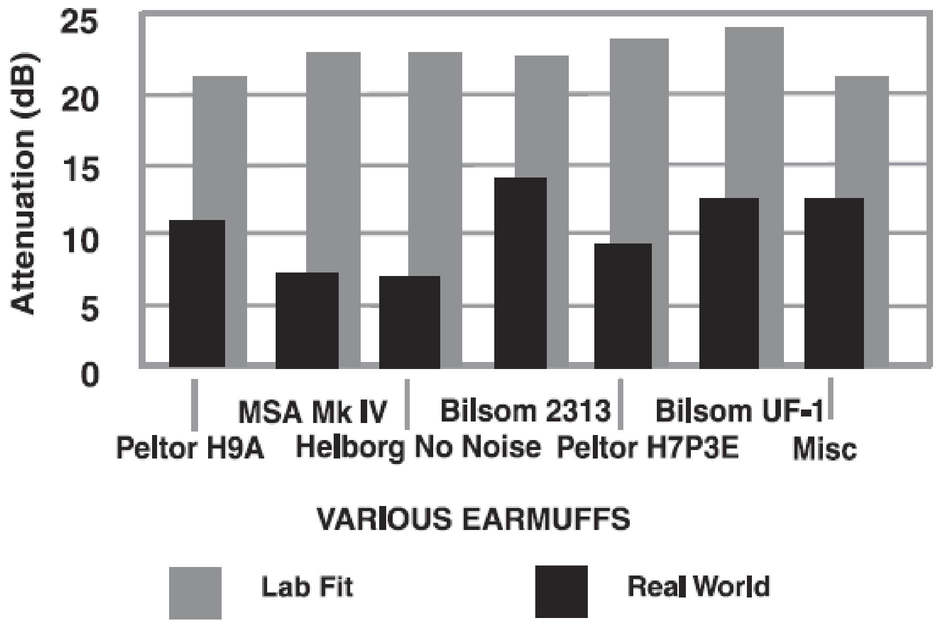

Abb. 5: Die Dämmwerte verschiedener am Markt verfügbarer Kapselgehörschützer unter Laborbedingungen (grauer Balken) und unter realen Bedingungen bei Schusslärm (schwarzer Balken). Auffällig ist, dass alle getesteten Gehörschützer weniger als 20 Dezibel Lärmreduktion erreichen [aus 4].

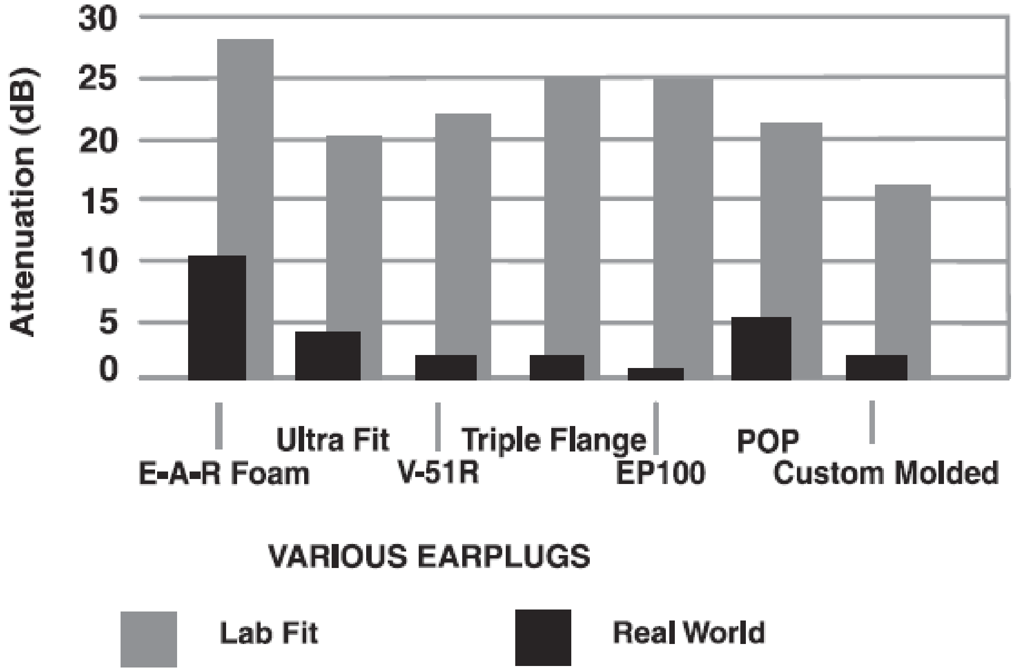

Abb. 6: Die Dämmwerte verschiedener am Markt verfügbarer Gehörschutzstopfen unter Laborbedingungen (grauer Balken) und unter realen Bedingungen bei Schusslärm (schwarzer Balken). Auffällig ist, dass alle getesteten Gehörschützer weniger als 20 Dezibel Lärmreduktion erreichen [aus 4].

Schalldämpfer reduzieren nur den Mündungsknall und haben keinen Einfluss auf den durch Überschallgeschwindigkeit des Projektils verursachten Geschossknall. Daraus wurde teilweise abgeleitet, dass Schalldämpfer nur einen geringeren Schutz als Gehörschützer bieten können, da der Schütze dem Überschallknall weiterhin ausgesetzt bleibt. Dies ist in der Praxis aber nicht richtig. Der Überschallknall breitet sich kegelförmig hinter dem Geschoss in Flugrichtung aus, ähnlich der Kielwellen eines im Wasser fahrenden Bootes (Abb. 7). Er erreicht den Schützen ausschließlich durch Reflektion an Hindernissen im Bereich der Flugbahn. Da der Schallldruck sich im Raum in alle Richtung ausbreitet und dabei sehr schnell verringert, werden durch den Geschossknall unter Feldbedingungen keine gesundheitsschädlichen am Ohr des Schützen erreicht.

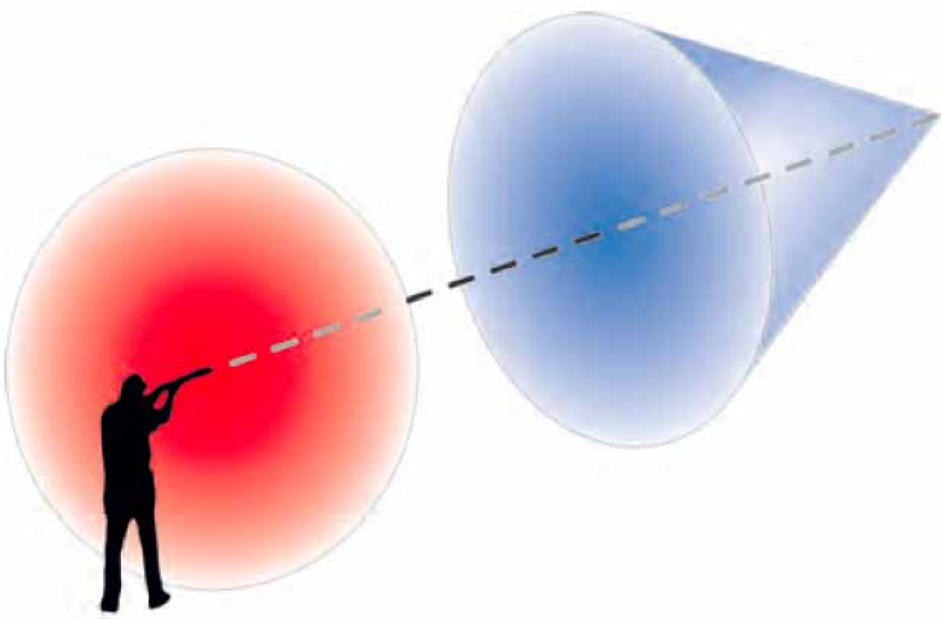

Abb. 7: Mündungsknall (rot) und Geschossknall (blau) schematisch dargestellt. Der Geschossknall breitet sich in Flugrichtung aus und wirkt nicht direkt auf den Schützen ein [aus 1].

Teilweise wird auf elektronischen Gehörschutz verwiesen, da dieser eine Lärmreduktion auf 84 Dezibel o. ä. bieten würde. Dieser Verweis geht fehl, es handelt sich um ein Mißverständnis. Elektronischer Gehörschutz (auch „Aktivgehörschutz“ genannt) verfügt über ein außenliegendes Mikrofon und einen innenliegenden Lautsprecher, der auflaufende Geräusche an das Ohr weitergibt. Erreichen die ankommenden Geräusche ein gesundheitsschädliches Niveau, werden sie entweder gar nicht mehr oder nur gemindert weitergegeben. Viele Geräte ziehen diese Grenze bei 84 Dezibel. Dies bedeutet jedoch nicht, dass kein Lärm über 84 Dezibel das Ohr erreicht: wenn die Elektronik keine Geräusche mehr weitergibt, wirkt auch der elektronische Gehörschützer letztlich nur wie ein passiver Gehörschützer. Wie hoch die Dämmung ist, hängt von der Bauweise ab. Sie liegt jedoch nicht über der von baugleichem passiven Gehörschützern.

Schlussfolgerungen:

1. Schalldämpfer entfalten konstruktionsbedingt zuverlässig ihre Schutzwirkung, die je nach Modell und genutzter Kombination aus Waffe und Munition etwa 20 bis über 30 Dezibel erreicht. Dies deckt sich mit Messungen des Autors, bei denen im Kaliber .30 die besten am Markt verfügbaren Dämpfer Dämpfungswerte von 30 Dezibel und mehr in der Messung nach MIL-STD erreichten.

2. Die Dämmwirkung von Gehörschützern hängt konstruktionsbedingt vom korrekten Sitz und dem konkreten Lärmereignis ab. Bei Schusslärm erreichen Gehörschützer regelmäßig erheblich schlechtere Dämmwerte, als bei den Messungen nach DIN EN 352 oder ISO 4869. Die angeführten Studien zeigen, dass unter Feldbedingungen Dämmwerte von deutlich unter 20 Dezibel eher die Regel als die Ausnahme sind.

3. Diese Differenz ist bei Gehörschützern in den dargestellten wissenschaftlichen Untersuchungen damit so hoch, dass die im Arbeitsschutz vorgesehenen Grenzwerte für Impulslärm beim Schießen mit schalenwildtauglichen Patronen nicht eingehalten werden können.

4. Schon eine einmalige Lärmexposition über die im Arbeitsschutz vorgesehenen oberen Auslösewerte für Impulslärm bringt die Gefahr einer Gesundheitsschädigung mit sich.

5. Es bestehen angesichts der Studienlage begründete Zweifel, dass alleine durch den Einsatz von Gehörschützern diese Grenzwerte unterschritten werden können.

Christian Neitzel

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Chapter 29

International Review of Field Studies of Hearing Protector Attenuation

Elliott H. Berger, John R. Franks, and Fredrik Lindgren

When a manufacturer designs a hearing protection device (HPD), a hearing conservationist specifies its use, or a purchaser selects it for a particular application, one question foremost in their minds is just how much noise reduction (also called attenuation) the device will provide. Until the middle 1970s this question was always answered using test data obtained under closely controlled conditions in a laboratory setting. The degree to which such data corresponded with actual use, often called "real-world" performance, was not only unanswered, but also rarely if ever asked. This changed in the latter part of the 1970s as studies began to appear in the literature that presented the results of attenuation experiments conducted in the real world. Subjects in the studies were persons actually wearing HPDs for protection from occupational noise.

Although there have been at least 22 reported studies worldwide since 1975, that have examined real-world attenuation of HPDs,[1–22] and a review paper published in 1983 that summarized the data from the 10 studies available at that time,[23] controversy still exists concerning real-world attenuation. The debate centers around the extent of the divergence between values measured in the laboratory under ideal and commonly standardized conditions and those values observed in the real world, and how to best use laboratory data to predict real-world performance for particular applications. Herein we update Berger's 1983 summary, and provide a definitive picture of the real-world attenuation of hearing protectors circa 1994. We also present representative laboratory test data so that its validity (or realism), that is, the accuracy with which it predicts real-world performance, can be assessed.

Estimation of effective protected noise exposures when hearing protectors are worn not only requires valid HPD attenuation data, but also accurate noise exposure measurements as well as a suitable computational scheme with which to utilize such values. Noise measurements and predictive methods are not the subject of this chapter, but the results of such computations are of course heavily influenced by the attenuation data described herein. A recently issued ISO standard[24] describes three computational approaches. The reader is also encouraged to review Lundin[25] and Waugh[26] for background analyses and discussion.

Real-World Data Sample

The first reported data on field performance of HPDs appeared in 1975.[19] Since then, we are aware of at least 21 additional studies available worldwide.[1–18,20–22] The total data base comprises results from over 90 different industries, in seven countries (Argentina, Canada, Finland, Germany, Netherlands, United Kingdom, and United States) with a total of approximately 2900 subjects.

Field measurements have been conducted by independent researchers, government-sponsored investigators, and staff employed by the industries supplying the data. In all cases, the test subjects were workers or military personnel exposed to noise who were tested in most cases while wearing their own HPDs.

The facilities that have been studied most likely represent the better hearing conservation programs in existence. This presumption is based upon the increased likelihood of finding higher quality programs among companies and organizations interested in and choosing to participate in the complicated, time-consuming, and costly research of the type required for real-world evaluations. In fact in at least two of the more recent studies, the locations were selected specifically because the authors believed them to be exemplary.[9,18]

Candid Versus Scheduled

Subject participation in field studies has been based upon either *candid* selection or *scheduled* testing. Candid studies are the type in which subjects know that their work site is under investigation and that they will be asked to participate, but they do not know when. The researcher selects them without warning and then escorts them to the test facility while monitoring them to assure that they do not readjust the fit of their HPDs. Scheduled tests describe situations in which either the subjects are notified in advance and asked to come to the test facility bringing their HPDs with them to fit at the time of the test, or may be of the type where subjects are fitted with earmuffs instrumented with small microphones to measure the interior and exterior noise levels while they wear their HPDs during the work day.

At face value it might seem that candid studies would provide a truer picture of actual real-world usage than would scheduled studies. For the scheduled test it would appear axiomatic that the subject would purposely fit the device differently, a better fit because the testing is under the watchful eye of the experimenter or the subject wants to look good; a poorer fit because the subject wants to sabotage the test results.

For four of the insert HPDs evaluated, there were enough studies of both types to examine the effect of scheduling. Although for three of the earplugs, the scheduled tests tended to show higher attenuation values by a few decibels in terms of the Noise Reduction Rating (see Real-World Data and Metrics Utilized in This Report), the candid and scheduled data agreed within a few tenths of a decibel for the device on which the largest number of studies were conducted (E·A·R®/Decidamp earplugs, see Table 29-1). The foam earplug is also the one for which attenuation can be varied most easily and dramatically by subject-insertion method, and thus would have been anticipated to be the one most susceptible to bias on the part of the test subjects. For the remainder of this chapter, the data from both the candid and scheduled procedures will be pooled for analysis and discussion.

REAT Procedure

Two principal methods have been used to measure real-world attenuation: real-ear attenuation at threshold (REAT) and microphone in real ear (MIRE). For a complete discussion see Berger.[27]

REAT can be conducted with all types of hearing protectors as long as the facility presents the test signals in a sound field, even if the sound field is only that found in a small portable audiometric booth. However, because of potential background-noise masking problems, as well as cost and convenience considerations, it is generally easiest to conduct field REAT measurements using large circumaural earcups with built-in loudspeakers to generate the requisite sound field for the open and occluded measurements. Even so, masking of low-frequency open thresholds can occur. This will lead to underestimates of REAT. With headphone-based REAT procedures only earplug type HPDs can be evaluated.

Typically, under field application of REAT, a subject is first tested with the HPD in place as it was worn on the job, followed by an open threshold. The difference is the presumed real-ear attenuation. Because of possible learning effects between the occluded and open audiograms, the open threshold values may be spuriously improved by a few decibels simply due to better test-taking skills on the second test, and hence the REAT increased. This potential error, which can lead to overestimates of attenuation, is in the opposite direction to that caused by background-noise masking effects noted above.

An interesting alternative REAT procedure, the reference-earmuff method, was utilized in one study to measure earmuff and semiaural device attenuation.[21] The authors selected it because they were concerned about room noise producing masking of the open ear thresholds, which can easily occur under field test conditions. They sought a method like that of headphone-based REAT in which thresholds are always measured inside noise-excluding earcups. But, they wanted to be able to test earmuffs, an option that would be precluded by a headphone-based procedure.

The solution was to establish both real-ear attenuation and the occluded threshold levels for test subjects wearing a reference earmuff in the laboratory. In the field, measurements were taken of the occluded thresholds (no unoccluded values were measured in the field) for both the product being field tested (candid subject fit) and the reference earmuff (experimenter-supervised fit). The attributed attenuation was then calculated as the laboratory attenuation of the reference earmuff plus (or minus) the difference between the occluded thresholds of the reference earmuff and the test HPD, under field conditions. The accuracy of this method is strongly dependent upon the particular attenuation values selected for the reference earmuff, and the presumption that the attenuation of the reference earmuff achieved by the field test subjects closely approximates the values found in the laboratory using a different panel of listeners.

MIRE Procedure

The MIRE procedure, as implemented in field studies, consists of mounting small microphones inside and outside a hearing protector while it is worn by an employee on the job. The "test noise" is the actual noise to which the employee is occupationally exposed. The attenuation values that are reported can either be the differences in spectral sound pressure levels recorded by the two microphones, or the differences in time-averaged values of the A-weighted sound pressure levels (i.e., noise doses).

Because of the intrusiveness of mounting interior and exterior microphones, field MIRE measurements, unlike REAT, can only been applied to circumaural HPDs. The advantage of MIRE is that it allows a continuous monitoring of the noise levels, and an objective measurement independent of the subjects' ability to take an audiogram. The disadvantage is the limitation of being able to only test earmuffs, and the fact that the experimenter and the procedure may directly influence the subjects' use of the HPDs. This may enhance attenuation as a result of the additional attention the wearer receives, or reduce attenuation if the cabling and microphones interfere with the earmuff's ability to properly seal and block noise.

MIRE is best measured via an insertion loss (IL) protocol in which the sound levels in the canal are measured with and without the HPD in place. This directly corresponds to the paradigm inherent in REAT, and is how MIRE is normally implemented in the laboratory. However, for practical reasons the implementation of MIRE in field studies is always done with interior (canal-, or concha-measured) and exterior noise levels simultaneously recorded to yield a noise reduction (NR) value instead of an IL value.

In the NR protocol the reference microphone is the exterior microphone. It records lower sound levels than the ear canal mounted reference microphone used in the IL method, because it does not benefit from the amplification of the transfer function of the open ear. Thus, the difference between the occluded measurement (interior microphone) and the open measurement (exterior microphone) is less than occurs with IL procedures. Because most authors do not correct their field-measured MIRE values, they tend to provide low attenuation estimates, by about 5 dB or so, at and above 3 kHz.

Laboratory Data Base

For purposes of comparison to the field data summarized herein, various graphs and tables also provide the associated labeled test data based upon manufacturers' published North American laboratory results.

Laboratory testing of HPDs in North America is conducted in conformance with standards promulgated by the American National Standards Institute.[28,29] The procedures call for determining ***"optimum performance values** which may not usually be obtained under field conditions"* (author emphasis). Optimum performance values, as opposed to estimated real-world values, have historically been specified for laboratory testing because US standards groups have felt that those values could be more consistently replicated, and were useful for rank-ordering HPDs. However, current data as described herein, and reported by Berger[30] suggest otherwise. Nevertheless, ANSI S3.19/S12.6 type data *are the only **standardized values*** that regulators and manufacturers in the United States currently have available for labeling and informational purposes.

In Europe, testing has been conducted according to ISO 4869.[31] The procedure is essentially the same as in the American standards, but the subject fitting practices are described somewhat differently and have typically been interpreted in ways that yield lower laboratory attenuation values, especially for insert-type HPDs, than do the tests reported by manufacturers on the other side of the Atlantic ocean.[32] Sample European data appear in selected octave-band charts to follow.*

Real-World Data and Metrics Utilized in This Report

The data reported in the 22 field studies are mean attenuation and standard deviation values. It is those data that are graphically presented in the accompanying figures. The authors' values have been utilized as reported. If they measured NR and failed to correct the values to estimate IL, then the NR measures were reported. Only in one instance were the raw data adjusted.[9] In that case background noise measurements were available to confirm that the low-frequency open thresholds were masked, spuriously reducing the measured real-ear attenuation. The values were mathematically corrected.[33] In some cases where authors reported data at fewer frequencies than required for computation of the Noise Reduction Rating (NRR), the NRR was estimated based upon empirical relations between attenuation at key octave bands and overall attenuation.[30]

The NRR was selected as a simplified single-number metric of an HPD's overall real-world attenuation, because it is standardized for labeling purposes,[34] it has been in use for over a decade, and it is well known in the hearing conservation community. For a given set of data and a given theoretical percentage of the population protected, the NRR is approximately 3 dB less than the Single Number Rating (SNR), the single-number metric defined in the recently released international standard, ISO 4869-2.[24]

The *labeled* NRRs were computed per the US Environmental Protection Agency, by subtracting a 2-standard deviation (SD) correction from the mean attenuation values in order to estimate the minimum noise reduction theoretically achieved by *98% of the laboratory subjects (NRR_{98})*. The field data were computed in the same manner except that only a 1-SD correction was included, thus estimating the minimum attenuation achieved by *84% of the actual wearers (NRR_{84})*.

The 2-SD deduction required in the labeled NRRs (i.e., $NRR_{98}S$) causes many field-measured NRRs to become negative numbers. A smaller 1-SD subtractive correction can avoid this problem. A 1-SD correction is also more in keeping with the practices of most of the non-North American community. With more realistic test data (i.e., larger SDs) it provides a better balance between adequately

*In this report, European data consist of results taken from manufacturers' European published data sheets, as well as data from the Karolinska Institute, Stockholm, Sweden.

protecting a majority of wearers and avoiding overprotection of a minority. Additional justification for use of a 1-SD correction stems from consideration of the heightened impact of outliers when 2-SD corrections are used, the reduction of between-study variability when only 1 SD is accounted for, and the variability of the susceptibility of individuals within a population to noise-induced hearing loss.[35]

The issue of whether field attenuation data are suitably normal to apply Gaussian-based SD corrections was examined by comparing estimates of the actual 84th percentile, to those obtained by subtracting 1 SD from the mean attenuation values. The data consisted of five 50-subject, and one 100-subject, subject-fit attenuation data sets, for four earplugs and two earmuffs. Both over- and underestimates of the true 84th percentile occurred, with the average error being 0.5 dB and the maximum error 3.1 dB. Examination of the same question using the real-world data of previous reports,[8,10] leads to errors of typically <2 dB, with the maximum difference between the 84th percentile and a 1-SD estimate of that value, being 4.2 dB.

Tabular Overview

The authors were able to gather from the 22 reports nearly 100 sets of data on approximately 40 different devices, each data set being defined as the attenuation at one or more frequencies for one HPD for one group of subjects. The results for all of the devices, sorted into five insert and two circumaural categories (excluding three HPDs which did not easily fit into any of the groupings), and averaged across studies, are summarized in Table 29-1. Individual devices and/or subcategories were selected so that similar products were assembled together, and so that the number of subjects for each subcategory was greater than 30. Another requirement for a device to be individually listed in a row was that published US laboratory test data had to be available for inclusion in the data set. Data from 2879 subjects out of a total possible population of 2945 subjects are included in Table 29-1.

For each row, the number of studies contributing data as well as the total number of subjects are shown, along with the real-world NRR_{84} averaged across the group of studies noted for that row. The labeled NRR_{98} based upon manufacturers' North American published laboratory test results is also reported. The last column provides the relationship between the real-world NRR_{84} and the labeled NRR_{98} as a percentage. The field NRRs for earplugs yield only 5–52% of the labeled values (averaging about 25%), and for earmuffs, from 47 to 76% (averaging about 60%).

Representative Octave-Band Results

Representative field-performance data are presented in Figures 29-1–29-8, to illustrate the types of octave-band results observed in the various studies. The data include the results for: the earplug shown to provide the least attenuation under real-world conditions; an earplug with average real-world attenuation and very low interstudy variability; the earplug with the highest average real-world attenuation; and the earmuff on which the most real-world studies have been conducted. Figures 29-1, 29-3, 29-5, and 29-7 provide the individual data from each of the studies, and 29-2, 29-4, 29-6, and 29-8 present the data averaged across real-world studies with a comparison to both North American published manufacturers' data and representative European test data.

The results indicate that depending upon interpretation of the relevant test standard and implementation of subject selection, training, and fitting practices by the researcher, laboratory data may provide a more valid (European) or less valid (American) estimation of field performance. An American accredited standards working group, S12/WG11 (Field Effectiveness and Physical Characteristics of Hearing Protectors) as well as the National Institute for Occupational Safety and Health are cognizant of the problem and are currently conducting research and developing a new laboratory test method to address these issues.[36]

Table 29-1 Real-World (RW) Data Summary from 22 Independent Studies

Device Type	Device	No. Studies	No. Subjects	Mean RW NRR_{84} (dB)	Labeled NRR (dB)	NRR_{84}/ Labeled NRR (%)
Foam	E·A·R/Decidamp	15	633	13.4	29	46
Premolded	Ultra Fit	3	58	7.3	21	35
	V-51R	5	308	2.2	23	10
	Misc. 3-flange	2	31	4.5	26	17
	EP100	5	153	1.4	26	5
Fiberglass	Down	2	84	3.5	15	23
	POP	6	196	7.8	22	36
	Soft	3	80	4.7	26	18
Custom	Custom	6	447	5.4	17	33
Semiaural	Sound-Ban #10/#20	2	42	9.3	18	52
Earplugs (average)			2032	6.0	22.3	27
Earmuffs	Bilsom UF-1	2	41	16.3	25	65
	MSA Mk IV	4	89	10.8	23	47
	Peltor H9A	1	34	14.0	22	64
	Misc. Muffs	11	450	15.3	23	66
	Bilsom 2313	2	56	17.5	23	76
Cap-mounted	Hellberg No Noise	1	58	11.0	23	48
Earmuffs	Peltor H7P3E	1	36	13.0	24	54
	Misc. Cap Muffs	3	83	16.3	22	74
Earmuffs (average)			847	14.3	23.1	62
Grand average			2879	10.1	22.7	45

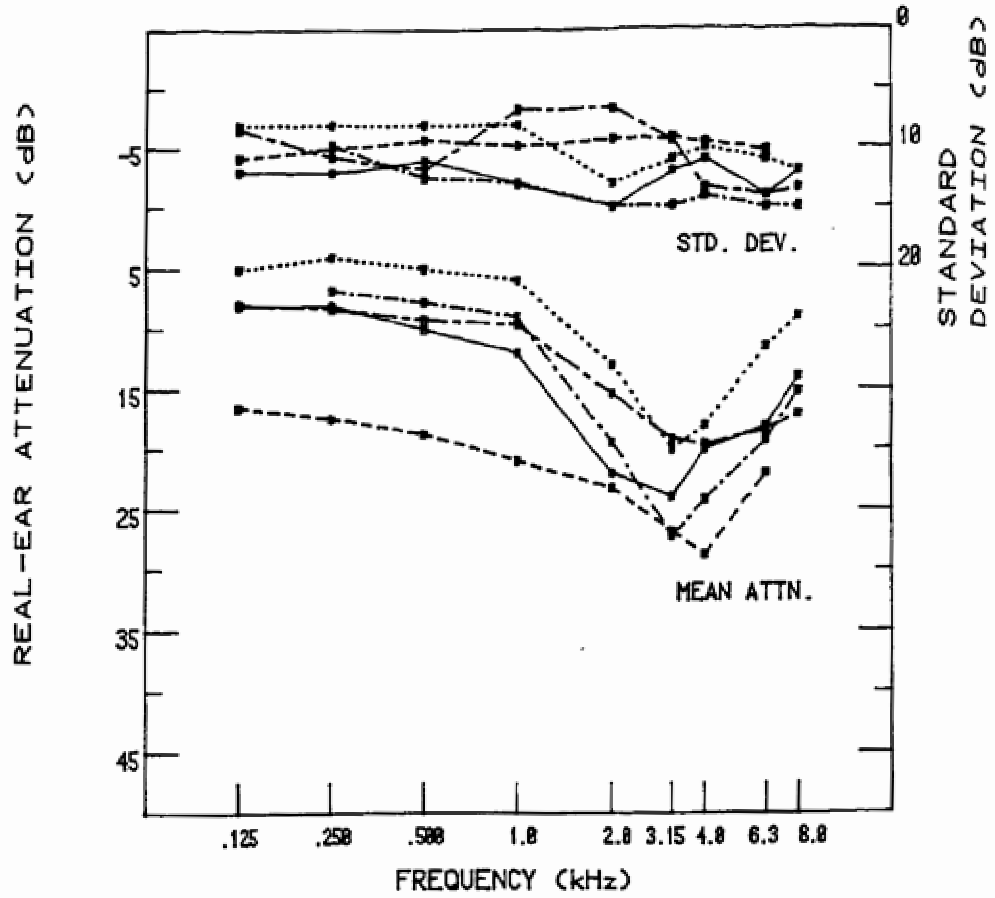


Figure 29-1 Real-world performance of the Willson EP100 premolded earplug (five studies, 153 subjects).

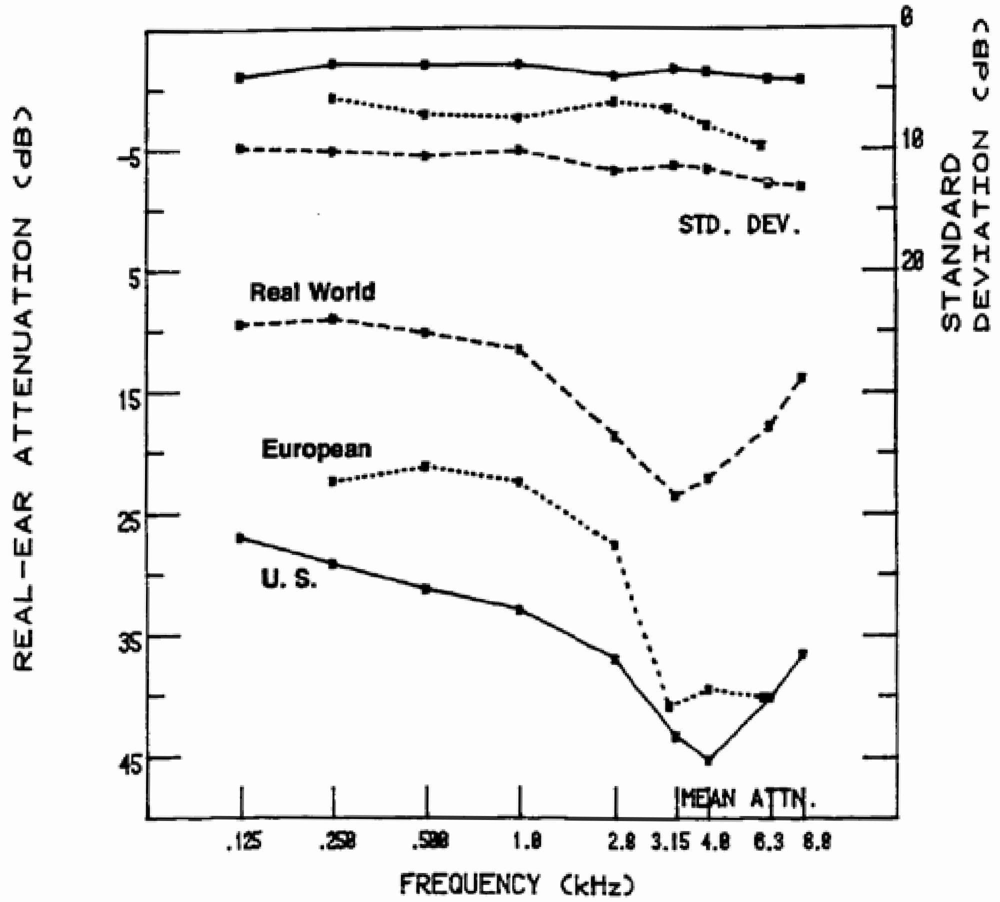


Figure 29-2 Willson EP100 earplug: real-world attenuation compared to manufacturer's US test data and European laboratory results.

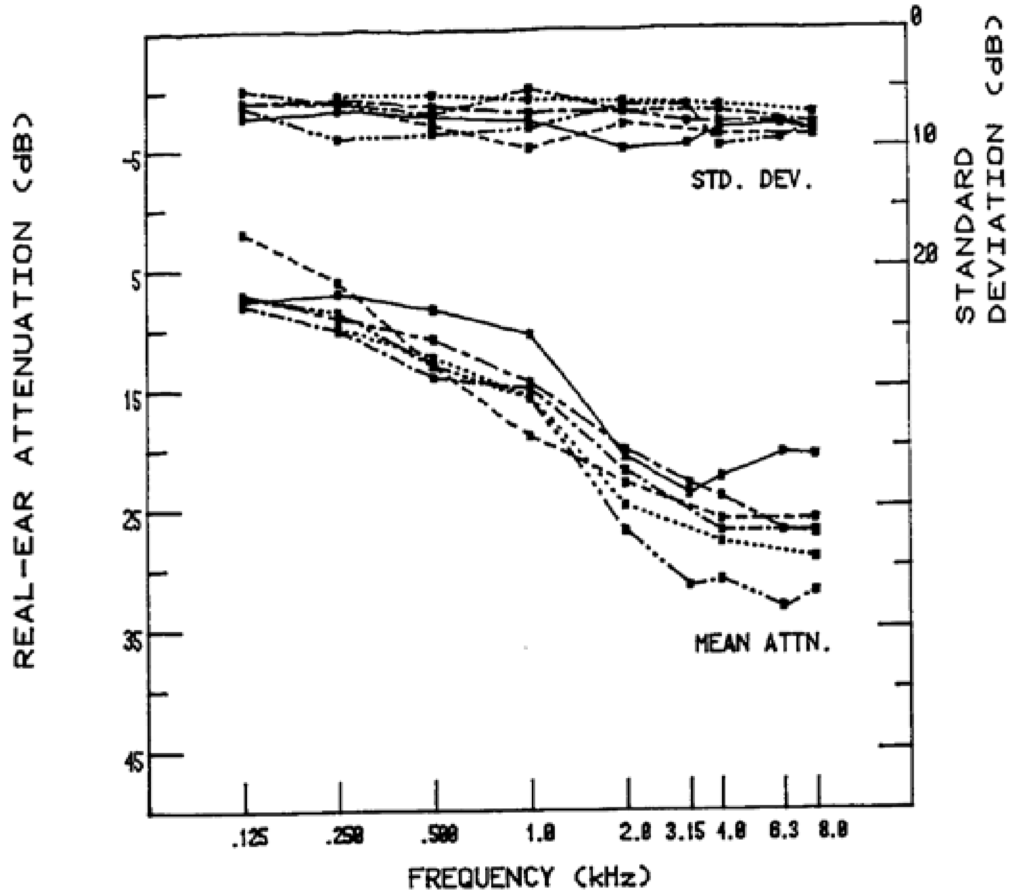


Figure 29-3 Real-world performance of the Bilsom P.O.P. sheathed fiberglass earplug (six studies, 196 subjects).

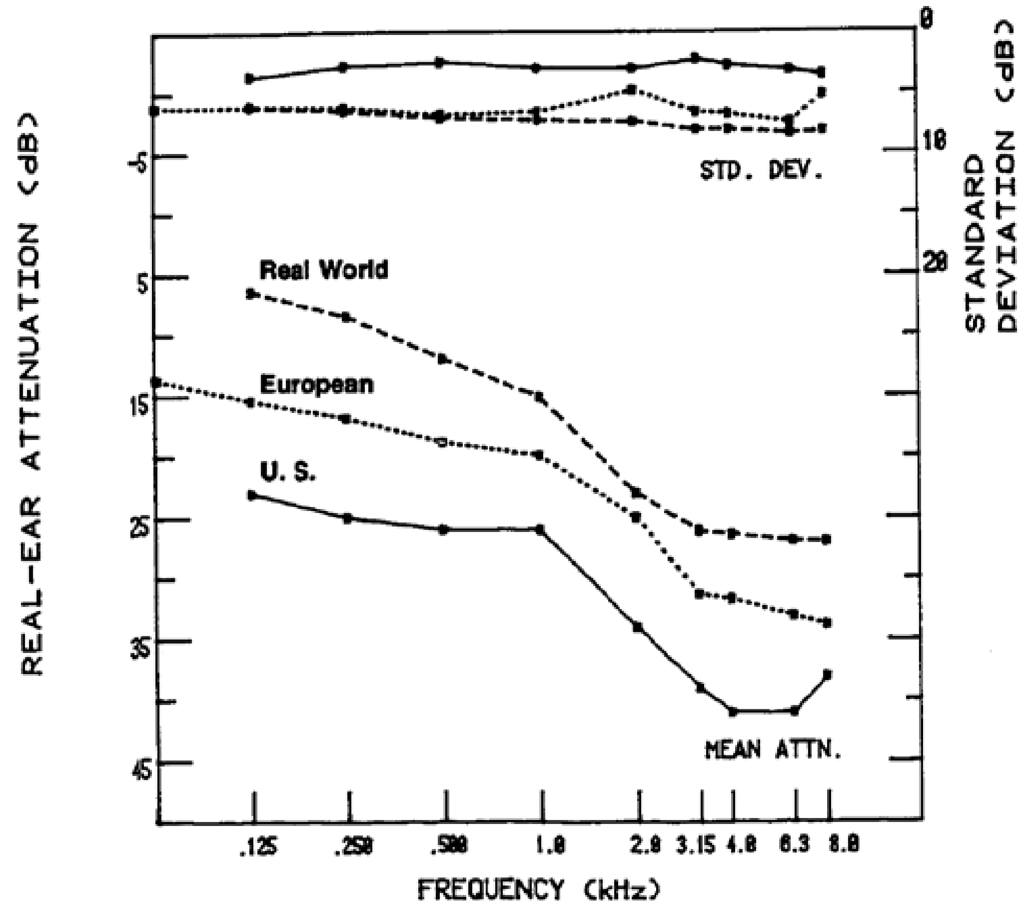


Figure 29-4 Bilsom P.O.P. earplug: average real-world attenuation compared to manufacturer's US test data and European laboratory results.

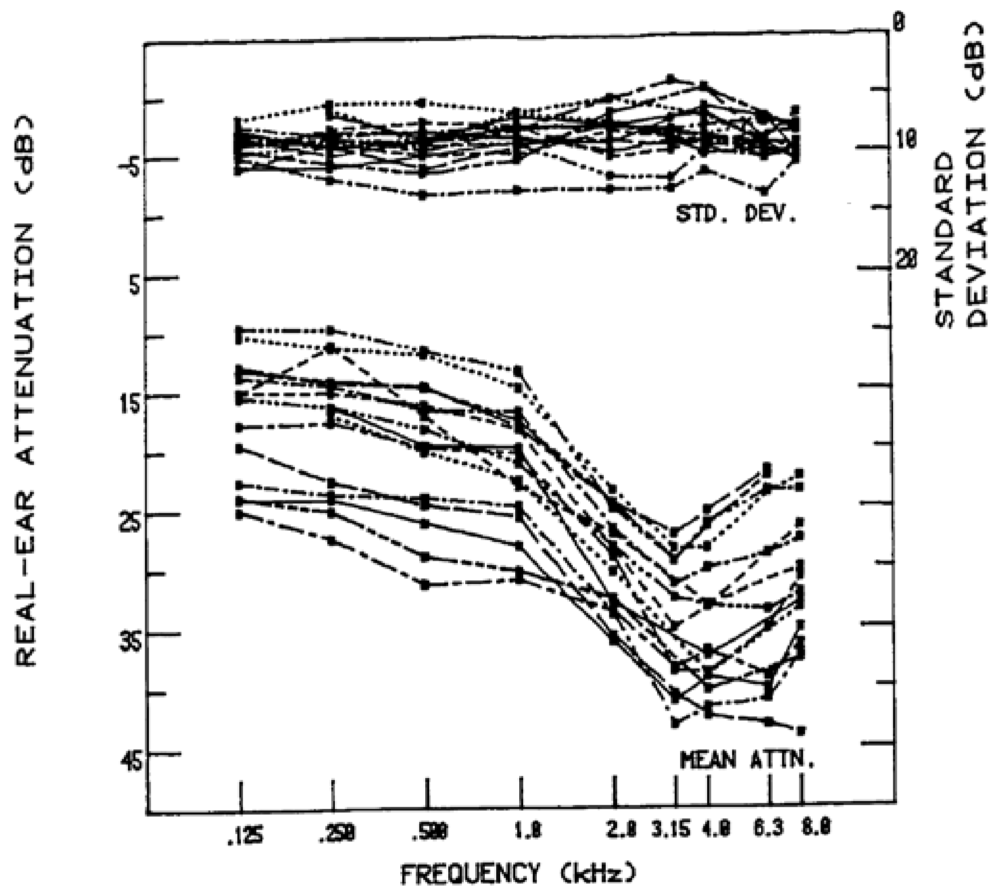


Figure 29-5 Real-world performance of the E·A·R/ Decidamp foam earplugs (12 studies, 633 subjects).

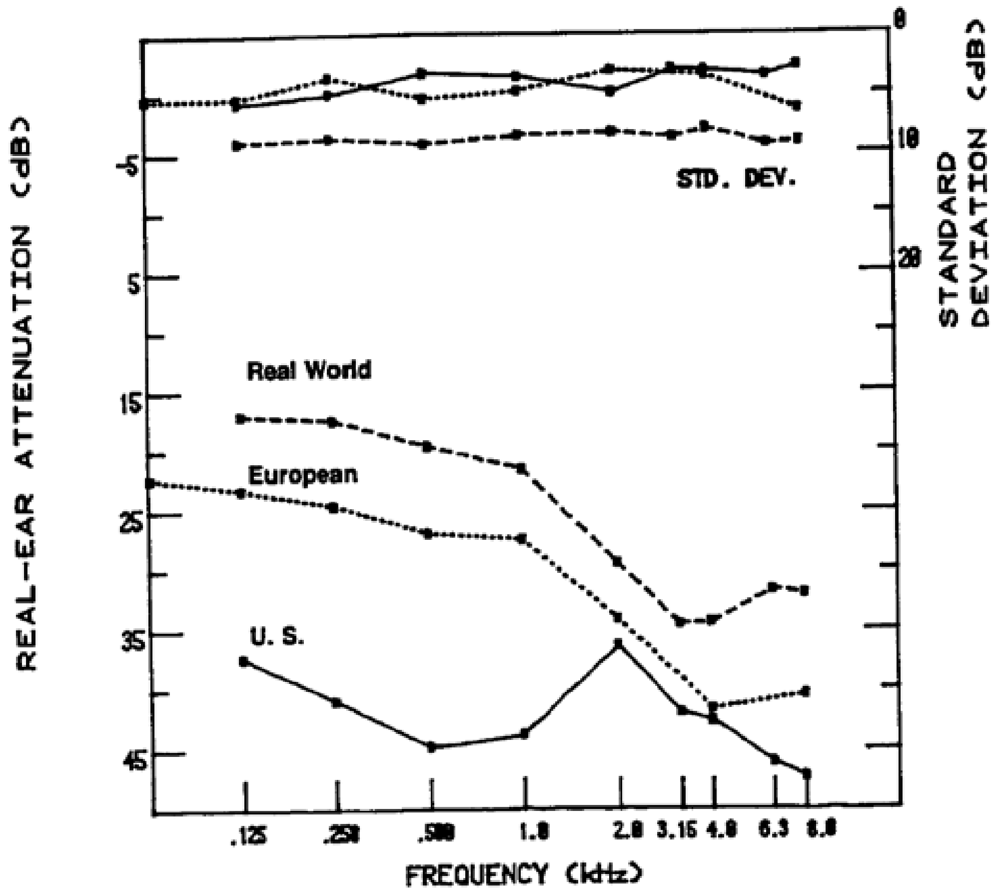


Figure 29-6 E·A·R/Decidamp earplugs: average real-world attenuation compared to manufacturer's US test data and European laboratory results.

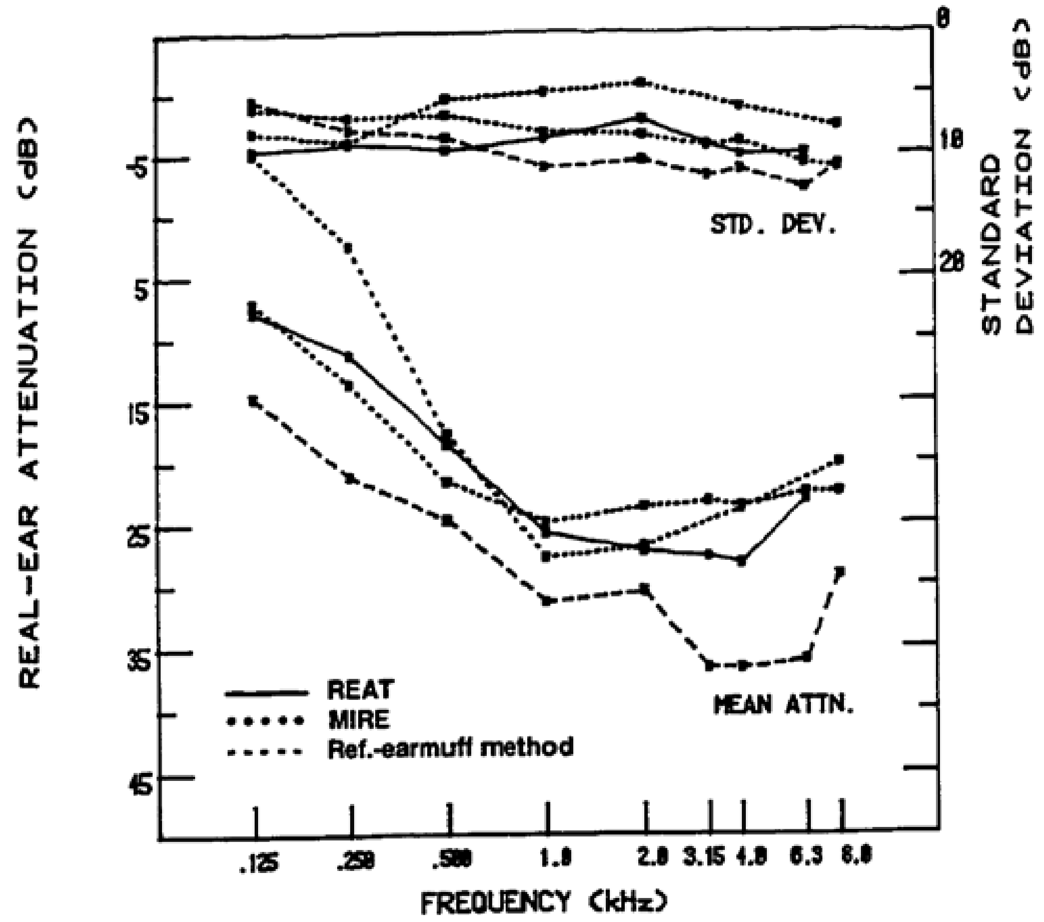


Figure 29-7 Real-world performance of the MSA Mark IV earmuff (four studies, 89 subjects).

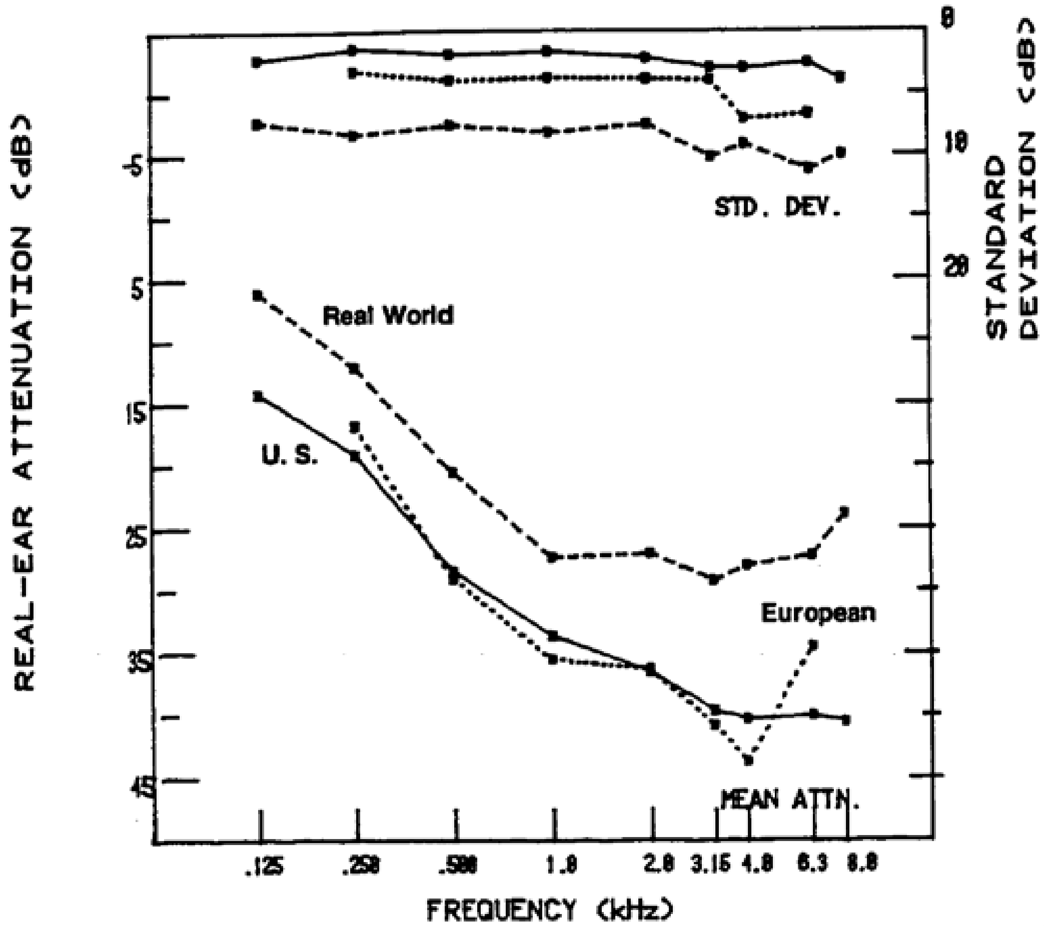


Figure 29-8 MSA Mark IV earmuff: average real-world attenuation compared to manufactrer's US test data and European laboratory results.

Following are specific observations about the data:

(1) Based upon real-world data, the lowest attenuating earplug among devices thus far tested, is the EP100. This is due to low mean attenuation values and high variability. Four of the five field studies agree rather closely (within 7 dB up through 2 kHz) (Figures 29-1, 29-2).

(2) The P.O.P. earplug exhibits a very tight range in mean attenuation values and SDs across field studies. The spread in data is about what would be expected from a typical interlaboratory as opposed to an interworkplace study (Figures 29-3, 29-4).

(3) The E·A·R/Decidamp earplug provides potentially high degrees of protection, but also a wide range of attenuation and SD values across 12 separate studies. The variability is probably due to the fact that foam plugs, although they seal the ear well regardless of insertion depth, can provide dramatically differing values of attenuation depending upon the depth of insertion. Insertion depth of foam earplugs is a parameter that is heavily influenced by subjects' training and motivation to properly use the product, and also may be affected by the amount of noise reduction the wearers require or desire. (Figures 29-5, 29-6).

(4) The earmuff data include measurements from three different types of studies. The fact that the data from the reference-earmuff method are the highest shown, may be due to the way in which those real-world employees actually wore their earmuffs, or may be experimental artifact as discussed earlier. The averaged earmuff results shown in Figure 29-8 are representative of those found for other earmuffs, with the exception of the real-world SDs that tend to be high for this particular product. The differences between US and European mean attenuation values are insignificant, but the SDs are higher for both the European and the real-world data than for the US results (Figures 29-7, 29-8).

(5) Figure 29-9 provides a comparison of standard headband earmuffs to hard hat attached earmuffs. Despite the dissimilarity in the way the two types of earmuffs interface to the head, no practical differences were found in their real-world performance, that is, mean attenuation values were within 2.6 dB, and SDs within 1.2 dB at all frequencies.

Real-world data and US test data were compared for three earplugs and one earmuff for which there were sufficient samples for analysis. The mean real-world attenuation values were found to be statistically significantly smaller, and the associated SDs significantly larger, than for US laboratory data. There was more degradation in earplug than in earmuff performance, as would be anticipated due to the greater difficulty in fitting and inserting earplugs than earmuffs, but the differences were unique to the HPD tested. A similar analysis was not performed for the European laboratory data. However, as has been previously observed,[32] they appear to provide a closer approximation to real-world values than do the US data.

REAT Versus MIRE

Figure 29-10 depicts the real-world data for more than 16 models of earmuffs separated into nine REAT (501 subjects) and four MIRE (315 subjects) studies. Four interesting observations are apparent:

(1) Over the middle frequencies from 500 to 2000 Hz, where both methods are devoid of experimental artifact, the mean attenuation results of the two procedures are in nearly exact agreement, despite the wide diversity of samples and studies that are combined to produce the averaged results. No evidence is seen of any aberration due to learning effects, which would have caused the REAT values to exceed the MIRE data.

(2) As is well-documented in the literature, REAT yields spuriously high values of attenuation at the low frequencies due to physiological noise masking the thresholds in the occluded condition, and hence inappropriately increasing the occluded/open threshold shift.[27] At such frequencies an ob-

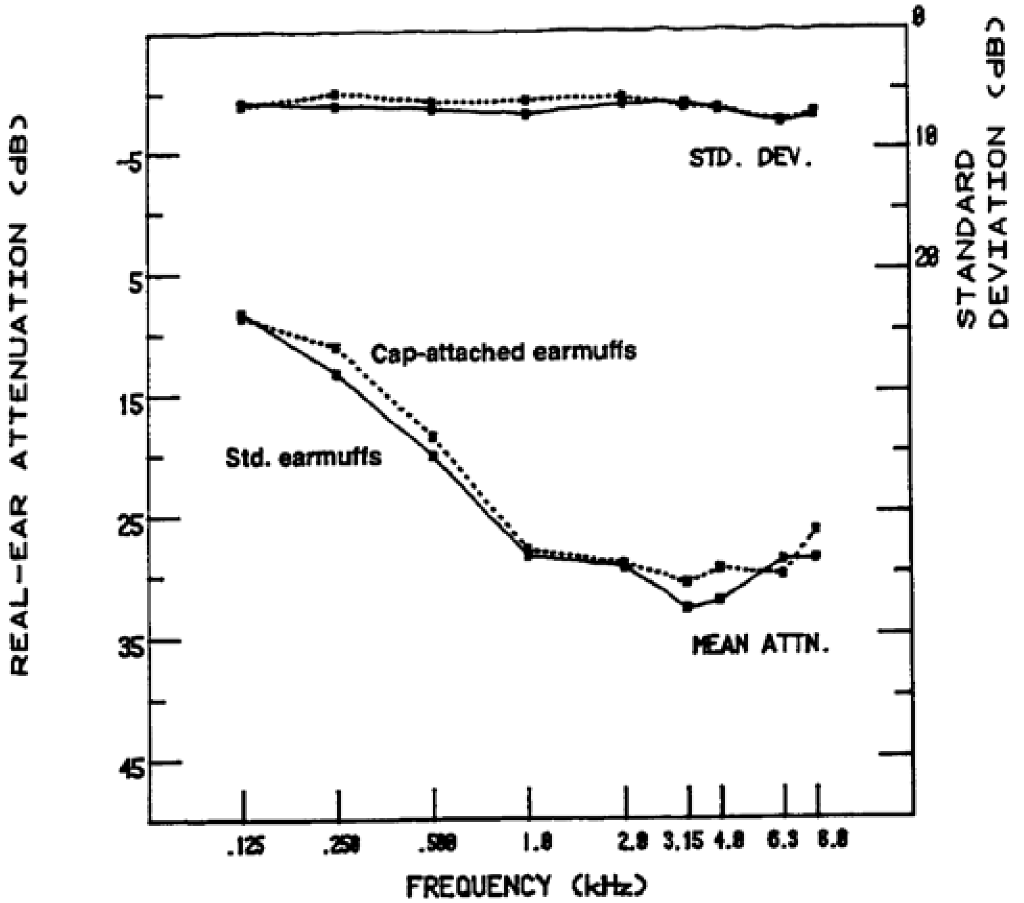


Figure 29-9 Comparison of standard earmuffs (eight studies, 324 subjects) to cap-attached earmuffs (four studies, 177 subjects) using real-world REAT data.

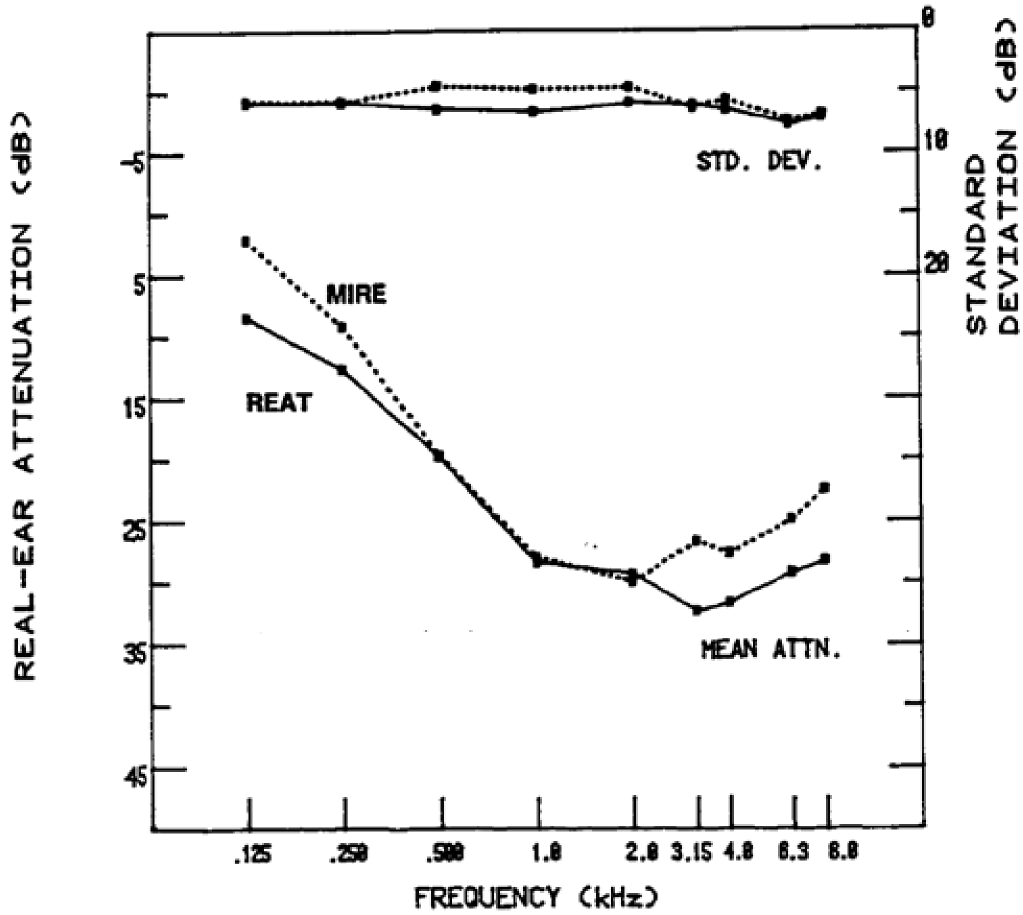


Figure 29-10 Comparison of real-world earmuff attenuation measured using REAT (nine studies, 501 subjects) and MIRE (four studies, 315 subjects) procedures.

jective measurement such as MIRE is more appropriate. The REAT/MIRE disparity in Figure 29-10 is seen to be from 6 to 3 dB at 125 and 250 Hz, respectively, in agreement with previously reported laboratory results.

(3) As discussed earlier, field implementation of the MIRE procedure is typically based upon NR instead of IL measurements, which leads to underestimates of attenuation above 2 kHz. This can be clearly noted in Figure 29-10. Therefore, REAT data, which are devoid of high-frequency artifact, provide the better assessment of attenuation at high frequencies.

(4) Concern is sometimes expressed that real-world REAT studies yield excessively high values of SD because subjects are not adequately trained in taking threshold audiograms, and thus their threshold variability contaminates results. If so, one would expect that an objective measurement such as MIRE, which does not include a threshold-variability component, would indicate lower SDs, and thus provide SD estimates more representative of the true variability in fit of the HPDs between subjects. This was not the case. At four of the seven test frequencies the SDs are essentially identical for both methods; from 500 to 2 kHz where differences exist, they amount to less than 2 dB.

Discussion

To more easily compare device types and gain a perspective of the attenuation attainable in the real world, data for three-flanged premolded earplugs, custom-molded earplugs, sheathed fiberglass earplugs, vinyl foam earplugs, and earmuffs, are compared in Figure 29-11. Foam earplugs provide the highest attenuation at 125 and 250 Hz and above 2 kHz, and earmuffs the most attenuation in the middle-frequency range, from 500 to 1000 Hz. In addition to the octave-band data, the NRR_{84} and the HML values[24] were also computed with a 1 SD correction and listed below the graph. They tell a similar story.

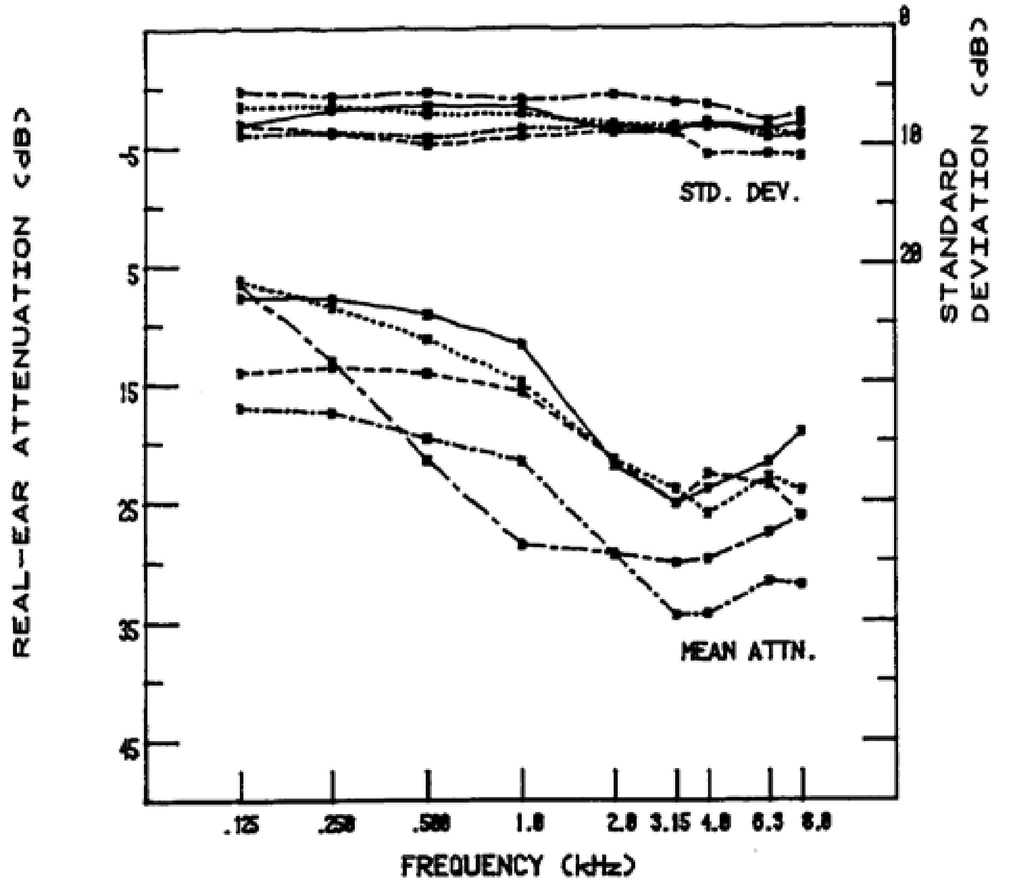
Note that the earmuffs show the smallest SDs at all frequencies, again confirming the greater ease with which they can fit, or be fitted by, a wide-ranging group of people.

The NRRs of the five device types were tested by a one-way analysis of variance, and found to have a significant device effect at $p < 0.001$. However, subsequent tests demonstrated that the custom-molded, fiberglass, and three-flanged groups were not significantly different at the $p < 0.05$ level, and that likewise the differences were not significant between the foam earplug and earmuff categories. Thus in terms of overall protection, the real-world data suggest that it is not possible to make fine distinctions between types of hearing protectors. To a first approximation only two categories can be distinguished: one consisting of the higher attenuation devices of foam earplugs and earmuffs, and the other consisting of lower attenuation devices comprised of the remaining principal types of (nonfoam) earplugs.

As an additional summary of the real-world data, Figure 29-12 provides an overview in terms of the field NRR_{84}s versus the manufacturers' published laboratory NRR_{98}s. The same trends emerge as were apparent in Figure 29-11. Measured as a percentage of the laboratory-rated attenuation, the field NRRs for earplugs yield only about 25% of the labeled values, and for earmuffs about 60%. It is especially clear that the American laboratory data not only provide a poor indication of the absolute values of field performance, *but of the rank ordering of those values as well*. This means that no single correction factor can be applied to existing laboratory data to estimate field performance. This is also demonstrated by the data in the last column of Table 29-1 that lists the real-world NRR_{84} as a percentage of the labeled NRR.

Especially misleading is the fact that the laboratory data would suggest that in general, earplugs provide the highest overall protection whereas, with the exception of foam earplugs, the reverse is true under field conditions.

Although the current report is intended primarily to provide a real-world data base for use in future research, it is instructive to discuss potential reasons for the divergence be-



Device Type	NRR$_{84}$	HML$_{84}$
Custom Molded	6	12 - 5 - 3
Sheathed Fiberglass	7	13 - 7 - 4
3-Flanged	7	12 - 7 - 6
Foam Plug	13	20 -13 -11
Earmuffs	15	23 -16 - 8

Figure 29-11 Summary of real-world data for hearing protectors separated into five categories.

tween laboratory data (primarily those of US origin) and field performance, most substantially for earplugs, but to a noticeable extent for earmuffs as well. The problem of predicting real-world performance has been extensively studied by S12/WG11 and has been the subject of research presentations as well as work in progress on a draft standard.[36]

A portion of the lab/real-world divergence is due to less than desirable quality in real-world hearing conservation practices in areas of fitting and training of HPD users, enforcement of proper HPD utilization, education and motivation of the work force, and program management. And the fact must be considered that user fitting of HPDs in the real-world is strongly affected by comfort, convenience, and interference with communications, whereas in the laboratory environment these parameters are considerably less important than attenuation.

Much of the divergence between laboratory and real-world data is also attributable to inappropriate laboratory practices and consequent unrealistic test results. It is just those practices, in the areas of subject selection, fitting, and training, as well as experimenter involvement and consistency across facilities, that are being addressed by S12/WG11. Based upon results of a four-facility interlaboratory study

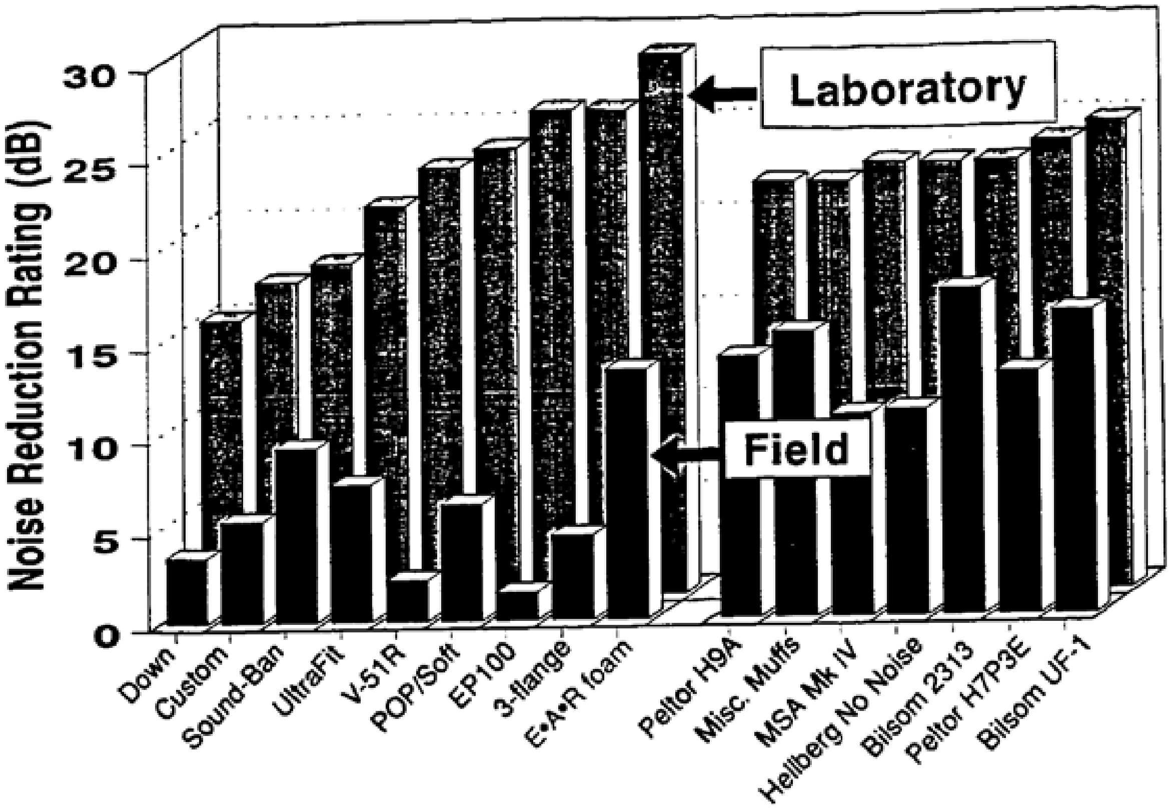


Figure 29-12 Comparison of NRRs published in North America (labeled values based upon laboratory tests), to real-world "field" attenuation results derived from 22 separate studies.

conducted under the auspices of the working group, there is optimism that a solution can be devised.[36]

Conclusions

Although the data base has grown substantially larger since the appearance of the earliest studies and summary reports,[23] the conclusions remain the same: real-world performance of HPDs, especially earplugs, demonstrates less attenuation and greater variability than currently standardized laboratory tests would predict. Measured in terms of the overall protection achieved by 84% of the workforce, earplug attenuation varies from a low of 1 dB for one type of premolded earplug to a high of 13 dB for foam earplugs, and about 11–17 dB for earmuffs.

Because field data are normally examined in terms of a value achieved by 84% of the users, the attenuation values appear quite low. However, field SDs are normally around 8–10 dB, and thus when the protection values are increased by 1 SD to estimate a mean value instead of an 84th percentile value, considerably larger amounts of attenuation are predicted. The selection of the statistical adjustment to include in the computation depends upon the goals of the specifier.

Field attenuation values are low enough that in many actual environments, even when only 10 dB of attenuation is required, it is questionable whether certain HPDs can provide the degree of protection needed for the majority of the workforce. Such findings may appear incredible to some observers, but the magnitude of the results is qualitatively supported by analyses of audiometric data from existing hearing conservation programs, and by real-world studies of temporary threshold shift.[37]

On a global basis there is no question that the existing group of 22 studies provides a clear indication of field performance, but additional data are required if specific guidance is to be developed for a wide variety of individual devices. HPDs that are in particular need of additional field studies are the semi-insert/semiaural types of hearing protectors as well as dual hearing protection, that is muffs and plugs worn in combination, the latter category for which (to the authors' knowledge) no published data on real-world attenuation are yet available.

Current research has demonstrated that a good estimate of the real-world attenuation achieved in the better programs can be obtained by testing *totally naive HPD users in a laboratory protocol with absolutely no individual training by the experimenter.*[36] When tested under those conditions, the attenuation of HPDs still equals or exceeds average real-world data of the type shown here. The fact that subjects completely untrained in the use of HPDs obtain more attenuation than occupationally exposed workers who would have been expected to be trained and motivated and to have benefitted from many months of practice in using their HPDs, is truly amazing! It suggests that today's typical, or even above-average hearing conservation programs, are ineffective in fully motivating and training employees to consistently and properly wear their HPDs.

Regardless of these issues and the research that is still needed to better define field performance possibilities, use of HPDs remains key to the prevention of occupational noise-induced hearing loss. If only hearing protection devices were worn properly and consistently, such causes of hearing loss would cease to exist.

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HEALTH & SAFETY LABORATORY

Assessment of firearm moderators (short report)

HSL/2004/01

Project Leader: **Elizabeth Brueck BSc MIOA**
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Science Group: **Human Factors**

CONTENTS

EXECUTIVE SUMMARY

OBJECTIVES

Large calibre rifles are used by the Forestry Commission for the culling of deer. These rifles produce high levels of noise in excess of the peak action level given by the Noise at Work Regulations. Hearing protection is used but the response of hearing protectors is difficult to predict when using firearms. There remains a risk with full-bore rifles that exposure while wearing properly selected hearing protection still exceeds 200Pa (140dB). Fitting moderators to these rifles reduces the peak noise level and the overall noise exposure, and it has also been claimed moderators reduce the recoil.

To assess the benefits of moderators measurements were made during the firing of nine different full-bore rifles and one .22 calibre rifle. Moderator models A, B and C were tested with full-bore rifles, model D on the .22 rifle. Only a limited range of moderators was selected for testing, as the intention was not to validate all the devices available but to find whether any were effective with the chosen rifle types.

MAIN FINDINGS

Without a moderator full-bore rifles gave peak sound pressures levels over 150dB(C). Only the smaller .22 rimfire gave peak levels below 140dB(C). The peak level under hearing protection could exceed the Noise at Work Regulation's 200Pa (140dB) Peak Action level as the effectiveness of hearing protection worn during firing was reduced by the recoil and muff movement.

Moderator A consistently reduced the peak noise level below 137dB(C). With this moderator full-bore firearms could be fired without hearing protection. A similar reduction was obtained in the vicinity of the person firing proving additional protection would be given to a dog, or an observer without hearing protection.

Moderators B and C were significantly less effective than moderator A confirming a wide variation between different designs.

With supersonic ammunition moderators gave little reduction in the noise at a distance in front of the firing point as noise from the bullet flight dominates. A reduction is only possible when subsonic ammunition is used but this is not recommended as a practicable noise control measure.

The recoil of the full-bore rifles was reduced by 20 to 30% with moderators A, B and C.

RECOMMENDATIONS

The highest peak level with moderator A fitted is just at the new Physical Agents (Noise) Directive action level of 137dB(C). Although not essential some lightweight hearing protection should be used in combination with this moderator when firing full-bore rifles, until the effect of age and use on the efficiency of the moderator is known.

1 INTRODUCTION

Large calibre rifles are used by the Forestry Commission for the culling of deer. These rifles produce high levels of noise, with peak levels in excess of 150dB. The peak action level given by the Noise at Work Regulations is 200Pa, equivalent to 140dB. This will also be the upper peak pressure limit in the Physical Agents (Noise) Directive (PA(N)D) (due to be adopted in February 2006), while hearing protection will be required at peak levels above 137dB(C). Under the current Regulations there is a duty to reduce the noise exposure of employees as far as is reasonably practicable by means other than the use of hearing protection.

The response of hearing protectors when using firearms is difficult to predict. There remains a significant risk that even with the use of hearing protection peak sound pressures are in excess of 200Pa at the ear. Moderators reduce the noise level, and it is claimed they also reduce recoil.

At the request of the Forestry Commission and the Health and Safety Executive (HSE), the Health and Safety Laboratory made measurements during the firing of full-bore rifles to assess the benefits of selected moderators. Three models of moderator were tested on full-bore rifles, identified as A, B, and C, and a measurement was made on a .22 rimfire with a fourth moderator, model D. Descriptions of each moderator are given in Appendix A.

Only a limited range of moderators were selected for testing, as the intention was not to validate all the devices available but to ensure a suitable moderator effective with the range of rifles was found. Measurements were made of the noise at the ear, both under and outside the muffs, the noise heard by a dog to the side of the man firing, and the noise heard by the quarry. The relative recoil with and without the moderator was measured with accelerometers fitted to the stock during firing.

2 MEASUREMENT METHOD

2.1 ON SITE RECORDINGS

Firing took place from a raised area, located part way up the side of a sheltered wooded valley that formed the firearms testing area. The raised area consisted of a mound of loose earth with a rough concreted area at the top. Carpet was placed over the concrete during the measurements to give some cushioning to the men firing. The weather was cool, with little wind. Eight professional forestry rangers provided and fired the rifles, five shots with the moderator fitted and five without. They each fired from the right shoulder, in a prone position and wore the earmuffs they normally wear when using rifles. These earmuffs were of a variety of types and ages.

2.1.1 Noise recordings

The noise outside the muffs was recorded with microphones held by the side of the head as shown in Figure 1. The noise under their muffs was recorded with miniature microphones fixed at the ear canal entrance as shown in Figure 2. Noise recordings were also made with tripod mounted microphones 2m to the side of the firing position and at a position 23m in front to assess the noise exposure of a dog and the noise heard by the quarry.

Figure 1 Measurements either side of the ranger's head

Figure 2 Miniature microphone on the ear for measurements under the muffs

The microphones and accessories used are listed below.

By the side of the ranger's head and 2m to the side at the position of a dog:

- Brüel & Kjær 4136 ¼ inch microphones with gooseneck extensions and windshields,
- Brüel & Kjær 2619 preamplifiers
- Brüel & Kjær 2804 microphone power supplies.

Under the ranger's muffs:

- Knowles CA 2832 miniature microphones powered from Brüel & Kjær 2804 microphone power supplies

23m in front of the firing position:

- Brüel & Kjær 4134 ½ inch microphone with gooseneck extension and windshield,
- Brüel & Kjær 2619 preamplifier
- Brüel & Kjær 2804 microphone power supply.

The outputs from the microphone power supplies were taken to two TEAC RD135T DAT recorders. These were set to 4-channel operation and double tape speed to allow recording up to 20kHz. A calibration was recorded for each microphone at the beginning and end of each day with a Brüel & Kjær 4226 sound calibrator set to provide a 1kHz, 114dB calibration tone.

2.1.2 Recoil recordings

Figure 3 Accelerometers fitted on stock

The acceleration associated with the recoil was recorded using two accelerometers fixed firmly to the end of the stock. The primary measurement was in the direction of fire; a second measurement was also made in a perpendicular direction. On the first day this was horizontally across the main axis of the rifle to record the sideways movement; on the second day the vertical direction was chosen.

The force of the recoil is dependent on both the acceleration and the mass of the rifle. The weight of each rifle was noted with and without the moderator fitted.

The recoil instrumentation is listed below:

- Brüel & Kjær 4393 accelerometers
- Brüel & Kjær 2635 charge amplifiers

The acceleration was recorded on the DAT recorders simultaneously with the noise. In addition a calibration for each accelerometer was recorded at the start and end of each day with a Brüel & Kjær 4294 vibration calibrator giving a 160Hz signal, with an r.m.s. acceleration of $10ms^{-2}$.

3 ANALYSIS OF THE RECORDINGS

Noise measurements were analysed by replaying the recordings through a Brüel & Kjær 2260 sound analyser.

3.1 PEAK SOUND PRESSURE

High peak sound pressures are hazardous to the ear. The Noise at Work Regulations aim to reduce the peak sound pressure at the ear to no more than 140dB. The Physical Agents (Noise) Directive sets a limit at this level and also requires hearing protection to be worn at peak levels above 137dB(C). The use of the C-weighting excludes frequencies outside the audible range.

The maximum C-weighted peak level in each series of five shots is reported here.

Above 126dB the miniature microphones under the muffs only measure positive sound pressures. Above 126dB the under muff results may be underestimated by up to 1dB because of this limitation. Below 126dB the microphones measure the full positive and negative pressure variations in the sound.

3.2 SOUND EXPOSURE LEVEL (SEL)

There is also a requirement to control the daily noise exposure arising from the number of shots fired in a day. The Noise at Work Regulations sets a first daily noise exposure ($L_{EP,d}$) action level of 85dB(A), and a second action level at 90dB(A). The Physical Agents Directive has action levels at an $L_{EP,d}$ of 80 and 85dB(A) and a limit at 87dB(A). Measurements are A-weighted to simulate the susceptibility of the ear to the frequency of the sound.

The sound exposure level (SEL) is the equivalent steady level over one second. It gives a measure of the total noise in a shot. The mean SEL of one shot in each five shot series is reported here. The $L_{EP,d}$ is calculated from the SEL using the following procedure.

$$L_{EP,d} = SEL + 10(\log N) - 44.6 \quad dB(A)$$

where N is the number of shots fired in a day.

SEL measurements were not possible under the muffs if the peak level exceeded 126dB due to the absence of the full negative pressure variations.

3.3 MEASUREMENTS FOR ESTIMATION OF HEARING PROTECTOR ATTENUATION

Hearing protector attenuation is frequency dependent. The difference in the C and A-weighted maximum sound pressure level measured with a Fast time constant ($L_{C,\ fast\ max} - L_{A,\ fast\ max}$) is used to estimate the frequency content of gunfire. According to EN 458:1993 the protector M-value is the predicted attenuation if the $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ value is less than 5dB. A revision of EN 458 due for publication in 2004 gives the M value minus 5dB as the predicted attenuation during gunfire.

A and C-weighted r.m.s. maximum levels recorded outside the muffs of the ranger firing were measured and the mean $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ result of each five shot sequence is reported.

3.4 RECOIL RECORDINGS

There is no recognised standard test for assessing the effect of recoil, so measurements have been based on the frequency range between 0.4Hz and 100Hz which is the range defined by ISO 2631-1:1993 for assessing exposure of the whole body to vibration or shock. The acceleration due to the recoil was measured by replaying the recorded signal from the accelerometers on the stock through a Larson Davis HVM 100 vibration meter. The measurements were band limited to the required frequency range but no additional frequency weighting was applied.

Both the maximum peak and maximum r.m.s. acceleration, obtained with a 1 second exponential time constant, were measured. The peak gives the highest instantaneous acceleration, the r.m.s. exponential time average maximum is dependent on both the level and duration.

4 RESULTS

Numbers and letters together with a brief description in the tables identify the moderators, firearms, and hearing protectors in these results. The names have been removed to avoid promotion of any particular device.

4.1 BY HEAD OF THE RANGER FIRING

Table 1 gives the sound levels measured by the side of the head and outside the muffs of the ranger firing.

4.1.1 Peak sound pressure levels

The measured peak level on the right was higher than on the left. Without a moderator all full-bore rifles gave peak levels in excess of 150dB on the right side of the head. The smaller .22 rimfire gave a peak level of 131dB without a moderator.

Moderator A reduced the peak level of full-bore rifles to below 137dB(C), giving a reduction in peak level of between 18 and 27dB. Moderators B and C gave no more than an 8dB reduction in peak level.

4.1.2 Sound exposure level (SEL)

Without a moderator the full-bore rifles gave an SEL between 118 and 124.5dB by the right ear. With Moderator A the SEL was 100.5 to 105.5dB(A). An SEL of 105.5dB(A) corresponds to a daily exposure ($L_{EP,d}$) of 85dB(A) after 257 shots and an $L_{EP,d}$ of 80dB(A) after 81 shots.

Without a moderator the .22 rimfire rifle gave a sound exposure level (SEL) of 91dB(A) at the right ear. 7,000 shots would have to be fired in a day to reach a daily exposure ($L_{EP,d}$) of 85dB(A) at the unprotected ear.

4.1.3 $L_{C,\ fast\ max} - L_{A,\ fast\ max}$

High $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values indicate low frequencies dominate the sound, low values indicate high frequencies dominate the sound. More high frequencies were heard in the shot when the moderator was fitted and low $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values reported for the measurements at a distance confirm this. By the head of the ranger there is a large spread in the $L_{C,\ fast\ max} - L_{A,\ fast\ max}$ values which suggest that when the moderator is used sounds from recoil and movement are adding to the measured sound as they are no longer masked by the shot.

4.2 UNDER THE MUFFS OF THE RANGER FIRING

Table 2 gives the results under the muffs of the person firing. Without the use of a moderator peak levels under the muffs sometimes exceed 140dB(C). Peak levels are consistently below 140dB(C) when any of the moderators are used. Table 3 gives the mean and range of the muff attenuation measured for each shot together with the muff M-value.

When a moderator is used the recorded attenuation of the muffs worn by the man firing has reduced. In the case of rifle number 7 the peak level under the muffs has even exceeded the peak level measured outside (shown by negative attenuation values in Table 3). Viewing of the waveform recorded under the muff cups shows frequencies below 50Hz are often dominating when the moderator is used. These low frequencies are due to movement of the muffs with the recoil, rather than the direct sound of the shot. This movement is also present when no moderator is fitted, but in this case the sound of the gunshot dominates. Analysis of the waveform under the muffs during the firing of rifle number 7 has also picked out a possible low frequency impact on the muffs, immediately following one shot.

4.3 AT A DISTANCE FROM THE RANGER FIRING

Table 4 gives the results for the recordings made 2m to the side and 23m forward of the person firing. Without a moderator peak levels 2m to the side are between 152 to 157dB(C). With moderator A these fell below 134dB(C), with reductions in the peak level of 26 to 29.5dB. Moderator A reduced the A-weighted SEL by between 18 and 22dB.

Moderators B and C were less effective. They reduced the peak sound pressure by 12 and 10dB respectively 2m to the side and gave a reduction of around 10dB in the A-weighted SEL.

The moderators both at 2m and 23m distance reduced the $L_{C,\ \text{fast max}} - L_{A,\ \text{fast max}}$ values. This confirms the moderators are removing the low frequencies from the sound.

23m in front of the firing point there was little or no reduction in the peak sound level from the full-bore rifles when a moderator was used and no more than a 5dB reduction in the A-weighted SEL.

Moderator D gave a 24dB reduction in the peak level 2m from the ranger firing when used with the .22 rimfire rifle, and a 13dB reduction 23m in front of the firing point.

4.4 RECOIL

Table 5 gives the recoil results in the direction of fire. These include the weight of the firearm, the mean acceleration for the five shots, and a force reduction ratio consisting of the weight times the acceleration with the moderator to the weight times acceleration without. The results show that the recoil is reduced by 20 to 30% when the moderator is used. It should be noted that the actual force could not be calculated because the mass acting with the acceleration is only proportional to the recorded weight.

Table 6 gives the mean acceleration measured in the directions perpendicular to the direction of fire. The force associated with the acceleration in these directions is thought to be proportional to a much lower mass than in the direction of fire, so the measured acceleration is of less significance to the actual recoil force.

5 DISCUSSION

5.1 CAN HEARING PROTECTION ALONE PROVIDE ADEQUATE PROTECTION?

When no moderator is used muffs have sometimes proved inadequate against the peak levels from full-bore rifles. Peak sound pressures at the ear have exceeded 140dB(C). Most muffs gave considerably less protection than the M-value estimate, especially when the moderator was used. This suggests the attenuation is limited by noise produced under the muffs, due to movement of the muffs and impacts on the cups as the firearm recoils.

5.2 IS HEARING PROTECTION REQUIRED WHEN A MODERATOR IS USED?

Hearing protection was required when any of the full-bore rifles were fired without a moderator. Only the .22 rimfire rifle was quiet enough to be used without hearing protection.

With moderator A full-bore rifles could be fired without hearing protection. Moderator A reduced the peak sound pressure levels to below 137dB(C), while hearing protection is required by the Noise at Work Regulations when the peak level exceeds 140dB. Also with moderator A the worse case daily noise exposure ($L_{EP,d}$) would only exceed 85dB(A) if more than 250 shots were fired in one day.

When the Physical Agents (Noise) Directive replaces the Noise at Work Regulations hearing protection will be required when the peak level at the ear exceeds 137dB(C). This value is close to the highest peak level measured with moderator A. There may therefore be a benefit in maintaining the use of some lightweight hearing protection in combination with firearm moderators. Also no measurements have yet been made to determine whether the moderator efficiency reduces with age, so some precautions are advisable.

Someone in the vicinity of the person firing would not need hearing protection under the current Noise at Work Regulations or the Physical Agents (Noise) Directive if moderator A were used as the peak noise level 2m to the side was reduced below 134dB(C).

Moderators B and C did not give sufficient reduction in the peak sound pressure to allow full-bore rifles to be used without hearing protection.

5.3 NOISE EXPOSURE OF A DOG

Peak levels 2m to the side of the ranger firing are between 151 and 157dB for full-bore rifles without a moderator. With moderator A the peak levels were below 134dB(C) and the SEL was reduced by 18 to 22dB. Assuming the frequency weighting for human hearing may be applied to dogs the results show this moderator would considerably reduce the noise exposure of a nearby dog.

The peak level remained above 140dB when moderators B and C were used and the SEL was reduced by just 10dB. These moderators would provide less protection for a dog.

5.4 DISTURBANCE OF THE QUARRY

Moderators on full-bore rifles gave no reduction in the peak sound level 23m in front of the firing point and only a reduction between 2.5 and 5dB(A) in the SEL. At this distance the flight noise of the supersonic ammunition dominates over the gunfire both with and without a moderator.

It is difficult to predict whether the quarry will be less disturbed when a moderator is used as the sound heard is not significantly quieter. The sound from the bullet flight, without the sound of the gunfire may be more difficult to locate. With the moderator the sound contains less low frequencies and this may also alter how the quarry reacts to the sound.

There is a reduction in the gunfire noise at a distance in front of the rifle when subsonic ammunition is used. When moderator D was used with the .22 rimfire, there was a 13dB reduction in the peak and a 16dB in the SEL 23m in front of the firing point. This will be heard as a quieter sound by the quarry.

5.5 MODERATOR EFFECTS ON RECOIL

The peak level of the recoil reduces by 20% when both the moderators A and B are used, and the r.m.s. maximum reduces by 30%. Moderator C gave a 30% reduction in both the peak and rms maximum recoil force.

The acceleration in perpendicular directions has not been added to the recoil assessment because it is assumed this is rotational and associated with significantly less mass than the acceleration in the line of fire.

6 CONCLUSIONS

- Without the use of a moderator hearing protectors are required when firing full-bore rifles. Of the rifles tested only a .22 rimfire could be fired without hearing protectors. Hearing protectors which were predicted to provide adequate protection according to standardised methods, did not always reduce the peak exposure below 200Pa (140dB). Muff movement during firing frequently caused low frequency sound under the muffs and in addition at least one impact on the muff cups was recorded during recoil.

- With moderator A the peak level from full-bore rifles reached a maximum of 136.5dB(C) by the head of the ranger firing. The overall noise level was such that over 250 shots could be fired before the $L_{EP,d}$ exceeded 85dB(A). Under the Noise at Work Regulations hearing protection should to be provided, when the number of shots fired in a day exceeds 250.

- Hearing protection will be required at peak levels of 137dB(C) with the enactment of the Physical Agents Directive. Also whether moderator efficiency changes with age and use is unknown. The use of some lightweight hearing protection in conjunction with moderator A is therefore recommended.

- Moderators B and C did not provide sufficient reduction of the noise when fitted to full-bore rifles to permit use without hearing protection. The performance of different models of moderator is clearly variable. To comply with the Noise at Work Regulations there is a duty to reduce as far as is reasonably practicable the noise exposure of an employee; the more efficient moderators should therefore be preferred.

- Moderator A reduced the peak level by 26 to 29.5dB at the side of the man firing, and the sound exposure level (SEL) by 18 to 22dB. This moderator gives significant protection for a dog or another person in the vicinity. The reduction in level is sufficient to remove the need for a person nearby to wear hearing protection.

- Moderators gave no reduction in noise that arises from the bullet flight when it travels over the speed of sound. There is therefore little reduction in the peak level forward of the firing point.

- With subsonic ammunition moderator D reduced the peak and SEL of the noise forward of the firing point by 13 and 16dB respectively.

- Moderators A, B and C all gave a 20 to 30% reduction in the recoil of full-bore rifles.

7 REFERENCES

The Noise at Work Regulations 1989 Statutory Instrument 1989 No 1790 – Health and Safety

Health and Safety Executive Reducing noise at work – Guidance on the Noise at Work Regulations 1989

Directive 2003/10/EC of the European Parliament and of the Council 6 February 2003 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (noise).

International Organisation for Standardisation ISO 2631-1:1985 Evaluation of human exposure to whole-body vibration

Pääkkönen and Kyttälä (1999) Report of Finnish Sound Suppressor Trials
www.guns.connect.fi/rs/trial1999.html

TABLES

Table 1 Sound levels measured by the side of the head during firing

Rifle no., calibre, ammunition and moderator	Maximum peak dB(C)		Mean SEL dB(A)		$L_{C,\ fast\ max} - L_{A,\ fast\ max}$ dB	
	Left	Right	Left	Right	Left	Right
Rifle # 1, .243, 100 grain						
Without moderator	149.5	155	114	120	3	1
With moderator A	128.5	131.5	99	100.5	-0.5	-1
Rifle # 2, .25-06, 90 grain						
Without moderator	153.5	155	118	121	3.5	2.5
With moderator A	135.5	136.5	102	105.5	9	-1
Rifle # 3, 6.5 x 55, 156 grain						
Without moderator	151	See	115.5	See	2.5	See note
With moderator A	130	note 1	99	note 1	7.5	1
Rifle # 4, .270, 130 grain						
Without moderator	150	153.5	115	119.5	1.5	4
With moderator A	130.5	131	99.5	101	1	1
Rifle # 5, .270, 150 grain						
Without moderator	153	154.5	119	121.5	3	1
With moderator A	135.5	135	101	103	0	-1
Rifle # 6, .308, 123 grain						
Without moderator	150	153	114	118.5	0.5	1.5
With moderator A	129.5	133	97	100.5	3	0.5
Rifle # 7, .308, 123 grain						
Without moderator	See	158	See	122	See note	1.5
With moderator A	note 2	130.5	note 2	100.5	2	2
Rifle # 8, .22 rimfire, 117 grain low velocity						
Without moderator	See	130.5	See	91	See note	11.5
With moderator D	note 2	127.5	note 2	84.5	2	21.5
Rifle # 9, .25-06, 117 grain						
Without moderator	156	159	122.5	124.5	2	2
With moderator B	151	153	116.5	118.5	1	0.5
Rifle # 10, .270, 130 grain T-mantle						
Without moderator	148	152.5	113.5	118	4	5.5
With moderator C	140	149	103	106	4.5	11

Note 1 Recorded levels were thought to be too low to be correct when compared with measurements in other positions.

Note 2 The microphone showed a drop in sensitivity of 9.6dB when recalibrated at the end of the second day's measurements. The results for these last two rifles tested before calibration have not been reported as the measured level appears effected by the changing sensitivity.

Table 2 Sound levels measured under muffs during firing

Muff, volume, and type	Rifle no., calibre, ammunition and moderator	Maximum peak sound pressure dB(C)		Mean SEL dB(A)	
		Left	Right	Left	Right
Muff N, small volume, passive	Rifle # 1, .243, 100 grain Without moderator With moderator A	 142 121	 146 122.5	 82	 82.5
Muff T, small volume, sound restoration	Rifle # 2, .25-06, 90 grain Without moderator With moderator A	 See note 2	 141 122.4	 See note 2	 84.5
Muff O, small volume, sound restoration	Rifle # 3, 6.5 x 55, 156 grain Without moderator With moderator A	 138.5 119.5	 142.5 124	 87.5	 87.5
Muff P, large volume, passive	Rifle # 4, .270, 130 grain Without moderator With moderator A	 137.5 113	 136.5 126	 72.5	 75
Muff N, small volume, passive	Rifle # 5, .270, 150 grain Without moderator With moderator A	 143 125.5	 139 122	 90.5	 91.5
Muff P, large volume, passive	Rifle # 6, .308, 123 grain Without moderator With moderator A	 134 118.5	 131.5 119.5	 71	 71.5
Muff Q, large volume passive	Rifle # 7, .308, 123 grain Without moderator With moderator A	 139 123.5	 142 134	 -	 -
Muff T, small volume, sound restoration in passive mode	Rifle # 8, .22 rimfire, 117 grain low velocity Without moderator With moderator D	 110 102.5	 117.5 113.5	 73.5 66	 81.5 81.5
Muff S, large volume, passive	Rifle # 9, .25-06, 117 grain Without moderator With moderator B	 137 129	 140.5 131.5	 -	 -
Muff R, large volume, passive	Rifle # 10, .270, 130 grain T-mantle Without moderator With moderator C	 135 127	 138 132.5	 -	 -

Note 1 Rms values are not quoted where clipping of the microphone signal occurred.

Note 2 The measured peak levels exceeded 140dB when the moderator was fitted. These peak levels are higher than those measured outside the muffs. It is probable the microphone in the left ear was displaced throughout the measurements with the firearm 2.

Table 3 Muff peak attenuation

The mean peak attenuation is shown with the range in parenthesis.

Rifle no., calibre, ammunition and moderator	Peak attenuation dB		Muff M value dB	Muff, volume, and type
	Left	Right		
Rifle # 1, .243, 100 grain			Not available	**Muff N, small volume, passive**
Without moderator	7.5 (6, 9)	8.5 (7, 9)		
With moderator A	8 (5, 12)	10 (9, 10)		
Rifle # 2, .25-06, 90 grain			28	**Muff T, small volume, sound restoration**
Without moderator	-	14 (12.5, 16)		
With moderator A	-	13.5 (12, 15)		
Rifle # 3, 6.5 x 55, 156 grain			22	**Muff O, small volume, sound restoration**
Without moderator	12.5 (11, 14)	-		
With moderator A	9.5 (8, 11.5)	-		
Rifle # 4, .270, 130 grain			28	**Muff P, large volume, passive**
Without moderator	12.5 (11, 14)	16.5 (15, 17)		
With moderator A	9.5 (8, 11.5)	9.5 (4.5, 16)		
Rifle # 5, .270, 150 grain			Not available	**Muff N, small volume, passive**
Without moderator	10 (9.5, 11.5)	16 (15.5, 16.5)		
With moderator A	9 (6.5, 11)	14 (9, 17)		
Rifle # 6, .308, 123 grain			28	**Muff P, large volume, passive**
Without moderator	15.5 (14.5, 16.5)	21 (21, 22)		
With moderator A	11.5 (9.5, 15)	16.5 (14, 21)		
Rifle # 7, .308, 123 grain			28	**Muff Q, large volume passive**
Without moderator	-	16 (15, 18)		
With moderator A	-	-4 (-7, -2.5)		
Rifle # 8, .22 rimfire, 117 grain low velocity			28	**Muff T, small volume, sound restoration in passive mode**
Without moderator	-	13		
With moderator D	-	14		
Rifle # 9, .25-06, 117 grain			27	**Muff S, large volume, passive**
Without moderator				
With moderator B	19 (18.5, 20)	18.5 (17, 20)		
	22.5 (21, 23.5)	21 (20.5, 21)		
Rifle # 10, .270, 130 grain T-mantle			31	**Muff R, large volume, passive**
Without moderator	13 (12.5, 14)	15 (14.5, 15.5)		
With moderator C	13 (6, 17)	11.5 (6, 18.5)		

Table 4 Sound levels 2m to side and 23m in front of ranger firing

Rifle no., calibre, ammunition and moderator	2m to side			23m in front		
	Max peak dB(C)	SEL dB(A)	$L_{C,\ fast\ max} - L_{A,\ fast\ max}$ dB	Max peak dB(C)	SEL dB(A)	$L_{C,\ fast\ max} - L_{A,\ fast\ max}$ dB
Rifle # 1, .243, 100 grain						
Without moderator	154.5	117	1	142.5	108.5	2
With moderator A	125.5	95	-1	142.5	103.5	-1.5
Rifle # 2, .25-06, 90 grain						
Without moderator	157	119.5	2	145	110	3.5
With moderator A	133.5	101	-0.5	143.5	105	-1.5
Rifle # 3 6.5 x 55, 156 grain						
Without moderator	154.5	116.5	1	143.5	108.5	2.5
With moderator A	128.5	97.5	-1	143	105	-1.5
Rifle # 4, .270, 130 grain						
Without moderator	153.5	116	1.5	145	110	4.5
With moderator A	129	98.5	-1	145	105.5	-1
Rifle # 5, .270, 150 grain						
Without moderator	153.5	116.5	1.5	See note 1	See note 1	See note 1
With moderator A	129.5	97.5	-1.5			
Rifle # 6, .308, 123 grain						
Without moderator	151.5	114	1.5	147	110	3
With moderator A	126	94.5	-1	147	107	-0.5
Rifle # 7, .308, 123 grain						
Without moderator	153	116.5	1	146.5	109.5	3
With moderator A	124.5	95.5	-1.5	146.5	107	-0.5
Rifle # 8, .22 rimfire, 117 grain low velocity						
Without moderator	133	91.5	-1.5	131.5	96	-1.5
With moderator D	109	Too low	Too low	118.5	79.5	-1
Rifle # 9, .25-06, 117 grain						
Without moderator	153.5	116	1.5	See note 1	See note 1	See note 1
With moderator B	141.5	106.5	0			
Rifle # 10, .270, 130 grain T-mantle						
Without moderator	152.5	116	1	145.5	110	4
With moderator C	143	106	-1	145.5	106	-0.5

Note 1: The signal from the microphone 23m in front was lost on the first day during firing of the last two rifles, numbers 9 and 5.

Note 2 The rms sound pressure levels 2m from the firing point are not recorded for the Bruno fitted with the moderator as the noise from movement and rapid reloading masked the sound of the shot.

Table 5 Weight, acceleration, and relative recoil reduction with the moderator

Rifle no., calibre, ammunition and moderator	Weight kg	Peak ms^{-2}	Relative recoil	r.m.s. max ms^{-2} (1s time constant)	Relative recoil
Rifle # 1, .243, 100 grain					
Without moderator	4	590	0.8	33	0.7
With moderator A	4.7	390		20	
Rifle # 2, .25-06, 90 grain					
Without moderator	4	680	0.7	38	0.6
With moderator A	4.5	420		21	
Rifle # 3 6.5 x 55, 156 grain					
Without moderator	5.5	580	0.9	32	0.8
With moderator A	6	470		22	
Rifle # 4, .270, 130 grain					
Without moderator	4.5	overload		overload	
With moderator A	5	560		33	
Rifle # 5, .270, 150 grain					
Without moderator	4.5	760	0.8	45	0.7
With moderator A	5	550		28	
Rifle # 6, .308, 123 grain					
Without moderator	5	580	0.8	32	0.7
With moderator A	5.5	420		21	
Rifle # 7, .308, 123 grain					
Without moderator	5.8	380	1.1	23	0.8
With moderator A	6.3	370		16	
Rifle # 8, .22 rimfire, 117 grain low velocity		Recoil indistinguishable from movement between shots			
Without moderator	4				
With moderator D	4				
Rifle # 9, .25-06, 117 grain					
Without moderator	5.5	530	0.8	30	0.7
With moderator B	6	380		19	
Rifle # 10, .270, 130 grain T-mantle					
Without moderator	4.8	720	0.7	42	0.7
With moderator C	5.3	470		26	

Table 6 Acceleration perpendicular to direction of fire

Horizontal sideways motion

Rifle no., calibre, ammunition and moderator	Peak ms^{-2}	r.m.s. max ms^{-2} (1s time constant)
1 .243		
100 grain		
Without moderator	94	7.4
With moderator A	59	4.1
2 .25-06		
90 grain		
Without moderator	65	7.0
With moderator A	110	18
3 6.5 x 55		
156 grain		
Without moderator	40	5.5
With moderator A	28	4.2
5 .270		
150 grain		
Without moderator	64	7.5
With moderator A	38	5.9
9 .25-06		
117 grain		
Without moderator	58	6.0
With moderator B	29	4.9

Vertical motion

Rifle no., calibre, ammunition and moderator	Peak ms^{-2}	r.m.s. max ms^{-2} (1s time constant)
4 .270		
130 grain		
Without moderator	120	10
With moderator A	120	5.8
6 .308		
123 grain		
Without moderator	140	4.2
With moderator A	93	2.9
7 .308		
123 grain		
Without moderator	170	2.9
With moderator A	120	2.6
8 .22 rimfire	Recoil indistinguishable from movement between shots	
117 grain low velocity		
Without moderator		
With moderator D		
10 270		
130 grain T-mantle		
Without moderator	180	14
With moderator C	150	9.2

APPENDIX A MODERATOR DESCRIPTION

Moderator A - A sealed unit comprising a cylindrical steel sleeve containing an expansion chamber and a series of baffles. The expansion chamber is sleeved over the barrel and secured at 2 points; on a threaded area at the end of the muzzle and on bushing at the rear of the unit. The baffles extend slightly beyond the end of the muzzle.

Moderator B - A sealed steel cylinder containing a series of baffles. The unit is secured to a threaded area at the end of the muzzle and extends beyond the end of the muzzle.

Moderator C - A sectional unit comprising a cylindrical steel sleeve containing an expansion chamber and a series of baffles. The expansion chamber is sleeved over the barrel and secured at 2 points; on a threaded area at the end of the muzzle and on bushing at the rear of the unit. The baffles extend slightly beyond the end of the muzzle.

Moderator D - A .22 rimfire moderator comprising a sealed steel cylinder containing a series of baffles. The unit is secured to a threaded area at the end of the muzzle and extends beyond the end of the muzzle.

AMERICAN ACADEMY OF OTOLARYNGOLOGY–HEAD AND NECK SURGERY FOUNDATION

Otolaryngology–Head and Neck Surgery
144(6) 950–953

DOI: 10.1177/0194599811398872
http://otojournal.org
SAGE

Comparison of Muzzle Suppression and Ear-Level Hearing Protection in Firearm Use

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No sponsorships or competing interests have been disclosed for this article.

Abstract

Objective. To compare noise reduction of commercially available ear-level hearing protection (muffs/inserts) to that of firearm muzzle suppressors.

Setting. Experimental sound measurements under consistent environmental conditions.

Subjects. None.

Study Design and Methods. Muzzle suppressors for 2 pistol and 2 rifle calibers were tested using the Bruel & Kjaer 2209 sound meter and Bruel & Kjaer 4136 microphone calibrated with the Bruel & Kjaer Pistonphone using Military-Standard 1474D placement protocol. Five shots were recorded unsuppressed and 10 shots suppressed under consistent environmental conditions. Sound reduction was then compared with the real-world noise reduction rate of the best available ear-level protectors.

Results. All suppressors offered significantly greater noise reduction than ear-level protection, usually greater than 50% better. Noise reduction of all ear-level protectors is unable to reduce the impulse pressure below 140 dB for certain common firearms, an international standard for prevention of sensorineural hearing loss.

Conclusion. Modern muzzle-level suppression is vastly superior to ear-level protection and the only available form of suppression capable of making certain sporting arms safe for hearing. The inadequacy of standard hearing protectors with certain common firearms is not recognized by most hearing professionals or their patients and should affect the way hearing professionals counsel patients and the public.

Keywords

tinnitus, sensorineural hearing loss, noise-induced hearing loss, firearm suppression, hearing protection

Received September 15, 2010; revised December 20, 2010; accepted January 11, 2011.

Noise-induced inner ear injury is a substantial cause of preventable disability in the United States. Approximately 15% of Americans between the ages of 20 and 69 years—or 26 million Americans—have hearing loss that may have been caused in part by exposure to loud sounds or noise at work or in leisure activities.[1] Subjective tinnitus affects approximately 50 million Americans (12%-15% of the adult population)[2-4] and often accompanies sensorineural hearing loss in patients with a history of loud noise exposure.[5-9]

Recreational use of firearms is a significant cause of noise and related ear injury in America.[10] There are approximately more than 250 million privately owned firearms in the United States,[11,12] and the number increases about 4.5 million per year.[13] This rate of increase rose by 14% for 2007-2008.[14] Unlike industrial exposure, hearing protection during recreational firearm use is not regulated or enforced. This represents one of the largest neglected areas of advocacy for prevention of ear injury.

Ear-level hearing protection is poorly understood by patients and hearing specialists alike. Far from being a panacea, ear-level protection rarely, if ever, confers the level of protection or noise reduction ratio (NRR) advertised. NRRs are determined using laboratory tests in continuous noise (not impulse sounds such as gunfire) and are not useful for determining the actual level of protection achieved by a given individual in a particular environment.[15]

How much protection is afforded by ear-level protection? The National Institute of Occupational Safety and Health (NIOSH) recommends that earmuffs be considered to have 25% less NRR than stated and formable earplugs 50% less.[16] The most common commercially available ear protection has an advertised NRR of 19 to 25 dB. The highest rated NRR are 31 dB and are less common. The Occupational Safety and Health Administration sets 140 dB

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This article was presented at the 2010 AAO-HNSF Annual Meeting & OTO EXPO; September 26-29, 2010; Boston, Massachusetts.

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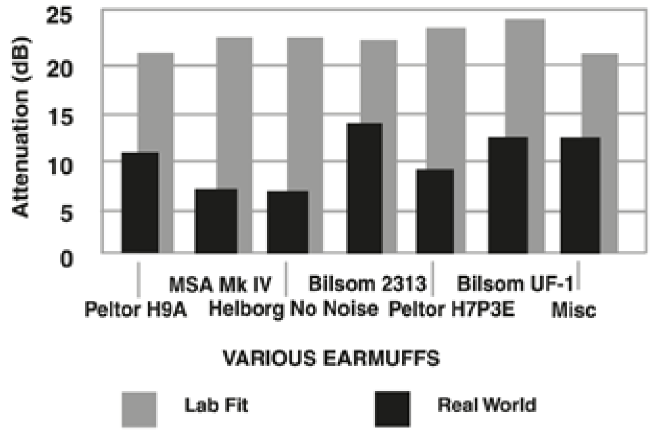

Figure 1. Noise reduction ratio (NRR) hearing protection provides in the real world: earmuffs.

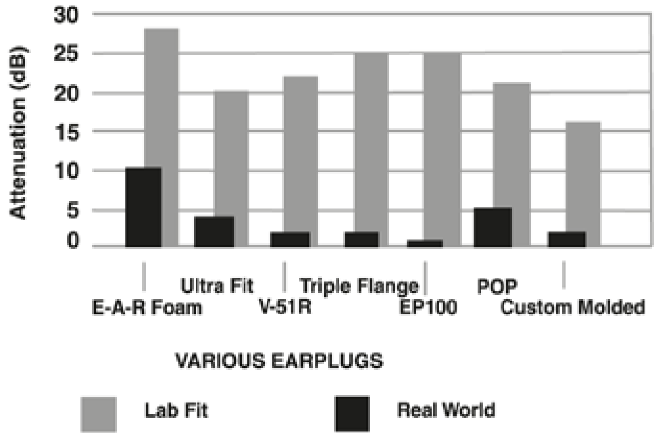

Figure 2. Noise reduction ratio (NRR) hearing protection provides in the real world: earplugs.

as the safe threshold for single-impulse sound exposure. Using the adjusted NRR levels, most hearing protection (NRR 19-25 dB) is unable to make hearing safe a firearm producing an impulse sound louder than 149.5 to 154 dB. The best available ear-level protection (earmuffs, NRR 31 dB) is unable to make hearing safe any firearm louder than 163 dB under the best of conditions. According to Berger et al,[16] even these adjusted figures are likely unrealistic. This review of 20 published studies demonstrated far worse performance than the corrected NRR suggests: the laboratory NRRs consistently overestimated the real-world NRRs by 140% to 2000% (**Figures 1** and **2**).[16] It is unlikely, however, that most consumers of hearing protection have any idea what the NRR is of the products they purchase or what level of protection is necessary to make their particular firearm safe for hearing.

Hiram Maxim first introduced and marketed muzzle suppressors in the 1920s in the United States. These devices either attach to the muzzle (by way of threading the barrel or by proprietary quick attachment mechanisms) or are integrated into the barrel. Muzzle suppressors allow the heated gases from the barrel to expand into a series of chambers or baffles, cooling and slowing the gas's exit from the barrel. The result is a shorter, quieter sound signature. The basic design of suppressors has changed little over the years, but modern design and manufacturing have improved their sound reduction effectiveness. Unlike ear-level protection, muzzle suppressors are relatively easy to use in a consistent, repeatable fashion. They confer protection for the shooter and bystanders alike and allow interpersonal conversation and situational awareness of sounds not afforded by ear-level devices. They are also legal in most states, although their ownership and transfer are regulated by the Bureau of Alcohol, Tobacco, Firearms and Explosives (BATF&E) and requires a $200 tax and somewhat lengthy process for registration, delaying use of the device for weeks or months from the time of purchase. Importantly, it is relatively simple to demonstrate their actual noise reduction capability compared with ear-level devices.

Study Design

We hypothesized that modern muzzle suppression has a demonstrable superiority to ear-level protection due to the unpredictable protection of ear devices and improbability of one-size-fits-all products. We tested common pistol and rifle calibers with and without muzzle suppression using strict military/industrial standard sound measurement for impulse noise. We recorded the impulse noise in decibels and compared the sound levels with and without suppression. We then compared the average noise reduction of the suppressors to likely NRR levels of ear-level products.

Methods

The tests were conducted using the Bruel & Kjaer (B&K) 2209 sound meter with a B&K 4136 microphone calibrated with the B&K 4220 Pistonphone. Calibration was checked after the tests to verify there were no shifts in calibration during the tests. All equipment has been certified and tested so that it can be traced back to the National Institute of Standards and Technology's standards. The meter and weapon are also placed in accordance with Military-Standard 1474D protocol. Five shots were fired to establish the unsuppressed level, and then 10 shots were fired with the suppressor attached.[17]

For the pistol tests, we used 9 mm and 45 ACP semiautomatic pistols (**Table 1**). These are very popular sporting rounds as well as common military standard calibers. The rifle tests were performed with a semiautomatic 5.56 mm/223 caliber round, as is used in the AR-15 style civilian rifle and the NATO military M16/M4 carbine rifle, and a bolt-action 7.62 × 51 mm/308 caliber rifle, also a common sporting round and NATO military standard round.

The suppressors used are commercially available and legally obtained by way of the standard BATF&E registration process for civilian ownership. No institutional review or ethics committee approval was deemed necessary or sought for this study.

Table 1. Firearms (Caliber, Manufacturer), Ammunition, and Suppressors Used

	Caliber	Manufacturer	Ammunition	Suppressor
Pistol	9 mm	Sig Sauer P226, Exeter, NH	Remington UMC 147 gr ball, Lonoke, AK	Advanced Armament Ti-Rant, Norcross, GA
	45 ACP	Glock 21, Smyrna, GA	Remington UMC 230 gr ball, Lonoke, AK	HTG Cycle-2, Boise, ID
Rifle	5.56 mm/223	Colt M4 16 inch barrel, Hartford, CT	M855 NATO 62 gr steel core penetrator, Independence, MO	Gemtech G5, Eagle, ID
	7.62 × 51 mm/308	Remington Model 700, Madison, NC	Remington 168 gr BTHP MK, Lonoke, AK	HTG M-30, Boise, ID

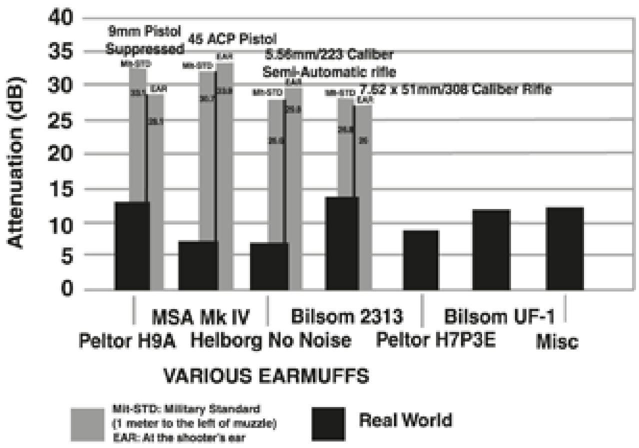

Figure 3. Firearm/suppressor attenuation compared with real-world earmuff attenuation. EAR indicates at the shooter's ear; MLT-STD, military-standard.

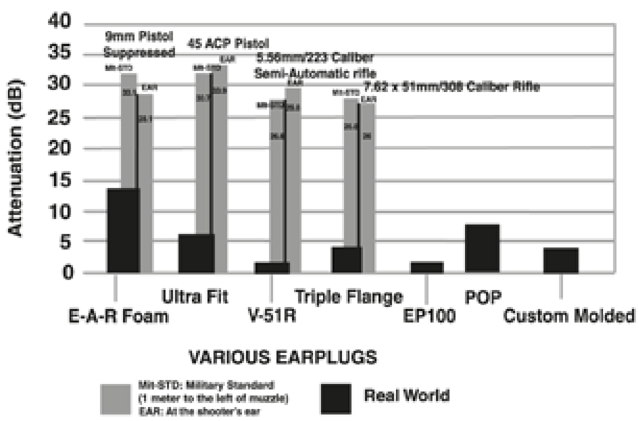

Figure 4. Firearm/suppressor attenuation compared with real-world earplug attenuation. EAR indicates at the shooter's ear; MLT-STD, military-standard.

Results

The average unsuppressed sound levels for the 9 mm pistol at military standard recording distance (1 m to the left of the muzzle) was 160.5 dB and 157.7 dB at the ear of the shooter. The average suppressed levels were 127.4 dB and 129.6 dB, respectively (difference of 33.1 dB and 28.1 dB).

The average unsuppressed sound levels for the 45 ACP pistol at military standard recording distance and the shooter's ear was 162.5 dB. The average suppressed levels were 131.8 dB and 128.5 dB, respectively (difference of 30.7 dB and 33.9 dB, respectively). The suppressor for the 45 ACP is also designed to function wet (filled with 10 mL of water for additional noise reduction). The average wet suppressed level was 121 dB (difference of 41.5 dB).

The average unsuppressed sound levels for the 5.56 mm/223 caliber semiautomatic rifle at the military standard recording distance was 164 dB and 155 dB at the shooter's ear. The average suppressed levels were 137.4 dB and 134.2 dB, respectively (difference of 26.6 dB and 29.8 dB, respectively).

The average unsuppressed sound levels for the bolt-action 7.62 × 51 mm/308 caliber rifle at the military standard recording distance was 165.7 dB and 157.2 dB at the ear. The average suppressed sound levels were 138.9 dB and 131.2 dB, respectively (difference of 26.8 dB and 26 dB, respectively). See **Figures 3** and **4**.

Discussion

The consistency of hearing protection use with recreational firearms is dismal.[18] We know that hearing compliance programs in industry rely on routine, supervised use of ear-level devices and periodic audiometric screening to assess effectiveness. No such programs exist for the recreational shooter. As the NIOSH Web site explains, the best hearing protection is the one the worker will wear.[16] But how do we motivate shooters to be compliant, especially in light of the data regarding the poor effectiveness of ear-level devices? Even compliant use of dual ear protection (plugs and muffs) over time leads to degradation of hearing.[19] Practical limitations of ear-level devices are myriad. Poor fit, migration of device due to activity or sweat, incorrect use, pain, heat, and loss of communication top the list.

Because of their use at the source of noise production, muzzle suppressors are much more effective at reducing noise. This facilitates communication and situational awareness, which can improve safety when operating firearms. Suppressors can easily and reliably be removed and transferred between multiple weapons of like caliber and reattached in a way that ensures proper fit and function. With suppression levels from 26 dB to 41 dB that are reliable and reduce impulse noise below 140 dB, all of the devices in our study are "hearing safe." However, weapon-suppressor combinations producing sound levels 130 dB or less (9 mm and 45 ACP wet) are much more comfortable to shoot without any hearing protection at all. In fact, the sound level of the 9 mm pistol's slide closing without any shot fired measured 124 dB. To our knowledge, this is the first time the efficiency of muzzle suppressors has been properly tested and compared with ear-level protection in any medical journal.

Conclusion

The muzzle-level suppressors studied on these weapons and calibers reduced sound levels well below the likely noise reduction of either earplugs or earmuffs.

Acknowledgments

The author thanks John Titsworth Jr, founder/owner of Silencer Research, LLC and SilencerResearch.com, for providing firearms, ammunition, suppressors, sound-testing equipment, and expertise in the performance of the testing described in this article.

Author Contributions

Matthew Parker Branch, original concept, experimental design and execution, research, writing, editing entire text, final approval.

Disclosures

Competing interests: None.

Sponsorships: None.

Funding source: None.

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