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QUALITY IN SPORT

eISSN 2450-3118 · Open Access · Peer-reviewed

apcz.umk.pl/QS Nicolaus Copernicus University in Toruń



SATŁAWSKA, Kamila, GOC, Artur, DRZEWIECKA, Julia, LASKOWSKA, Karolina, JASIELSKA, Lidia, DĄBEK, Karolina, GARBACZ, Katarzyna, WICZUK, Natalia, SIWKO, Michał and KANADYS, Szymon. Auditory Risk in Shooting Sports and Motorsport: Noise Exposure, Hearing Outcomes, Protective Practices and Evidence Gaps - A Narrative Review. Quality in Sport. 2026.78.76578. https://doi.org/10.12775/QS.2026.78.76578

ARTICLE TIMELINE

Received: 11.10.2026.
Accepted: 15.10.2026.
Published: 07.11.2026.

INDEXING & EVALUATION

MEiN points: 20 Unique ID: 201398
Disciplines: Economics & Finance; Management & Quality Sciences

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. Annex to the announcement of the Minister of Higher Education and Science of 05.01.2024 No. 32553. Unique Journal Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).

Punkty Ministerialne z 2019 — aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).

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Auditory Risk in Shooting Sports and Motorsport: Noise Exposure, Hearing Outcomes, Protective Practices and Evidence Gaps - A Narrative Review

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Abstract

Background. Competitive shooting and motorsport expose athletes to impulse noise and prolonged high-level sound.
Aim. To review noise exposure, auditory outcomes, audiological assessment and hearing protection in these sports.
Material and Methods. PubMed, Google Scholar and Web of Science were searched for studies published mainly in 2015-2026; relevant older studies and reference lists were also examined. Full texts were reviewed and findings synthesised narratively. Sport-specific evidence was prioritised.
Results. Noise exposure was substantial, but athlete-specific audiological evidence was limited and often cross-sectional. Findings included interaural threshold differences in shooters and hearing deficits in motorcycle racers; exposure was rarely linked to longitudinal outcomes. Conventional audiometry assesses hearing sensitivity, while the value of supplementary tests for routine athlete surveillance remains uncertain. Protectors and source controls reduced measured exposure under tested conditions. Practical challenges included consistent use, fit and communication. Laboratory studies found impaired localisation with protectors and partial improvement after training.
Conclusions. Prevention should reflect sport-specific exposure, protector fit and functional needs. Prospective studies combining exposure monitoring, repeated hearing tests and evaluation of protective practices are needed to inform surveillance and prevention.
Keywords: sport shooting; motorsport; noise exposure; hearing loss; audiological assessment; hearing protection.

1. Introduction

1.1. Noise as an Underrecognised Hazard in Sport

Noise exposure is a preventable cause of hearing impairment, but its recognition as a health hazard may be limited in environments where loud sound is an expected part of the activity. Shooting ranges and motor-racing circuits are examples of sporting settings in which participants and supporting personnel may repeatedly encounter potentially hazardous sound levels [8,12]. The relevant exposure extends beyond competition itself to training, preparation and time spent near other participants.
Evidence from occupational hearing conservation provides a basis for understanding noise-related injury and its prevention. However, applying this knowledge to sport requires consideration of the exposure pattern, equipment and practical demands of each discipline [26]. Reports of incomplete hearing-protection use among sport shooters

and motorcycle racers indicate that the availability of protective devices does not necessarily ensure their consistent use [11,16]. Hearing health therefore warrants consideration within the broader assessment of risks associated with training and competition.

1.2. Why Shooting Sports and Motorsport?

Shooting sports and motorsport provide two relevant settings for examining how different forms of acoustic exposure may affect athletes. Firearm discharge produces brief, high-amplitude impulses that recur throughout training and competition. Exposure is influenced by the weapon, ammunition and shooting environment, and includes shots fired by neighbouring competitors as well as those fired by the athlete [12,13].

Motorsport involves exposure sustained over practice sessions and races, with characteristics that vary across vehicles and racing conditions. Measurements at stock-car circuits have documented substantial noise exposure among drivers and team personnel [8]. In motorcycling, airflow around the helmet contributes to sound reaching the rider's ears, with experimental work identifying the region beneath the helmet near the chin bar as an important aeroacoustic source [9].

Considering these sports together allows discussion of both repeated impulse exposure and prolonged noise exposure without assuming that their risks are equivalent. Both also present practical challenges for prevention: hearing protection must be compatible with sporting equipment and the need to perceive relevant auditory information. Laboratory evidence that protectors can alter sound localisation illustrates this concern, although it does not establish an effect on competitive performance [5].

1.3. Current Evidence Gap

Evidence of hazardous acoustic exposure does not, by itself, establish the frequency or severity of hearing impairment in athletes. Sport-specific measurements describe the acoustic environment, whereas audiological studies assess hearing in selected groups; these approaches have often been applied separately [8,12,16,25]. Cross-sectional findings can identify hearing abnormalities or differences between ears, but cannot establish when these developed or isolate the contribution of sporting exposure.

Methodological inconsistency also affects the broader firearm literature. In their scoping review, Sonstrom Malowski et al. identified variation in outcome definitions, study protocols and assessment methods that prevented quantitative pooling of the evidence [24]. Findings from military personnel, hunters and recreational firearm users can inform assessment and prevention, but their applicability to competitive athletes requires separate consideration.

A sport-focused synthesis is therefore needed to connect exposure measurements, auditory findings and protective practices while distinguishing direct athlete evidence from supplementary research. This narrative review examines these areas in shooting sports and motorsport, considers the potential role of audiological surveillance, and identifies priorities for future research.

2. Materials and Methods

This narrative review was based on literature identified through targeted searches in PubMed, Web of Science and Google Scholar. Searches focused primarily on publications from 2015-2026, although older studies were also included when they provided relevant sport-specific evidence or addressed topics with limited recent research. The final search was conducted in September 2026. Various combinations of English-language search terms were used, including "shooting sports", "shooting athletes", "firearm noise", "motorsport", "racing drivers", "motorcyclists", "noise exposure", "impulse noise", "noise-induced hearing loss", "tinnitus", "hearing asymmetry", "audiometry", and "hearing protection".

Priority was given to studies involving competitive athletes and measurements conducted in sport-specific acoustic environments. Where athlete-specific evidence was limited, studies involving recreational firearm users, hunters, and occupational, military or laboratory populations were included to support the discussion of exposure characteristics, auditory effects and prevention. Their applicability to competitive sport was considered separately. Additional publications were identified by screening the reference lists of relevant studies and review articles.

Relevant full texts were examined, and information on study design, population, sample size, noise exposure, assessment methods, main findings and limitations was recorded. One study available only in Chinese was included and translated into English to enable assessment of its methods and extraction of relevant findings.

The evidence was organised into thematic sections covering noise exposure in shooting sports and motorsport, auditory outcomes, hearing assessment and preventive strategies. Findings were synthesised narratively because of differences in study populations, exposure measurements and outcome assessment methods. The review was not designed as a systematic review, and no quantitative meta-analysis was performed.

3. Noise Exposure in Shooting Sports

3.1. Characteristics of Impulse Noise

Shooting sports involving firearms are characterised by repeated exposure to high-intensity impulse noise. Measurements obtained during sport-shooting training and competition showed C-weighted peak sound pressure levels ranging from 138.2 to 165.2 dB, depending on the firearm and ammunition used [13]. However, peak sound pressure level alone does not fully describe a firearm impulse. The recorded signals lasted approximately 250-800 ms, whereas the period of highest transient acoustic power was approximately 1-2 ms [13]. This distinction between the overall signal duration and its brief high-amplitude component illustrates why exposure assessment should consider temporal and spectral characteristics, impulse duration and repetition alongside peak sound pressure level [13].

3.2. Cumulative Exposure During Training and Competition

Exposure in competitive shooting depends on both the characteristics of individual impulses and their repetition during training and competition. Individual training sessions described by Lwow et al. involved approximately 150-200 shots over 90 minutes. During group training, shots fired by neighbouring shooters also contributed to exposure, with an estimated 600-1350 impulses potentially reaching an individual shooter per session. The authors additionally estimated approximately 200,000 acoustic impulses over an annual training macrocycle [12].

These estimates reflect particular training patterns and should not be interpreted as universal exposure levels across shooting disciplines or as results of continuous individual dosimetry throughout a season. Nevertheless, they illustrate why counting only the shots fired by an athlete may underestimate the number of impulses reaching that athlete. Impulse counts should also be considered alongside the acoustic characteristics of the signals, since their number alone does not fully characterise exposure [12,13].

3.3. Influence of Firearm, Shooting Position, Distance and Environment

Acoustic exposure at the shooter's ear varies with firearm and ammunition characteristics, shooting position and the surrounding environment. In an acoustic study of 26 firearm/ammunition configurations used in youth target shooting, measurements were obtained at positions approximating a young shooter's left ear. For rifles and pistols, shooting from a seated position over a tabletop generally increased peak sound pressure levels and the eight-hour equivalent A-weighted sound pressure level (LAeq,8h) compared with standing shooting, although the effect varied across configurations [19]. These measurements illustrate how shooting position and nearby reflective surfaces can modify exposure; they did not directly assess hearing outcomes in young athletes[19].

The influence of firearm type also depends on the acoustic metric considered. In an acoustically treated indoor range, measurements at an instructor's position showed the highest A-weighted equivalent sound pressure levels during pistol firing, whereas the highest C-weighted peak levels occurred during shotgun firing. Increasing the instructor's distance from the shooters from 1.1 to 2.8 m was associated with an approximately 3-dB reduction in LAeq, followed by a further reduction of approximately 8 dB at 16.5 m [21]. These findings concern instructor exposure under specific range conditions and should not be directly extrapolated to athletes' ear-level exposure. Together, the studies support assessing the complete shooting environment rather than relying on firearm type alone [19,21].

3.4. Other Sources of Impulse Noise in Sport

Impulse noise exposure in sport also occurs outside competitive shooting, notably through starter pistols used to signal the beginning of races. An investigation of .22- and .32-calibre starter pistols included measurements in a simulated outdoor sprint-track setting. Peak sound pressure levels exceeded 140 dB at officials' positions and at the athlete positions nearest the source, with exposure varying by location and distance [18].

The authors identified particular concern for unprotected officials and people close to the pistols. Estimates based on an adult energy-based exposure criterion suggested comparatively low risk at the athlete positions examined, despite peak-level exceedances at the nearest positions. This distinction shows that risk estimates depend on the acoustic criterion as well as the exposure scenario. The findings therefore require separate consideration of officials' and athletes' positions and should not be interpreted as demonstrating universally safe exposure for athletes [18].

4. Noise Exposure in Motorsport

4.1. Sources and Characteristics of Motorsport Noise

Motor racing involves prolonged exposure to high sound levels during practice and competition. Engine and exhaust noise are important sources, while tyre–track interaction, mechanical components and airflow may also contribute. Wind turbulence was suggested as an additional contributor in open-cockpit Formula Ford cars, although its contribution was not measured separately. Prolonged exposure may also include high acoustic peaks: every monitored driver experienced a C-weighted peak sound pressure level exceeding 140 dB during at least one monitored race [14].

In motorcycling, airflow around and beneath the helmet also contributes to sound reaching the ears. Experimental investigation of these aerodynamic mechanisms complements measurements of the wider racing environment [9].

4.2. Direct Noise Measurements in Racing Drivers

Magara et al. monitored 10 racing drivers across five vehicle categories and four flag marshals. Eight-hour-normalised exposure levels (LAeq,8h) reached 112 dB(A) in both monitored V8 Supercar drivers and ranged from 101 to 104 dB[A] in the three Formula Ford drivers. Dosimeters positioned within 300 mm of the driver's ear characterised cockpit noise rather than sound levels beneath hearing protection [14].

An exploratory survey at three professional stock-car racing circuits included 24 area measurements and 26 personal dosimetry measurements. Monitoring of one driver on a practice day at Bristol Motor Speedway yielded an equivalent sound level [Leq] of 114.4 dB(A) and an eight-hour time-weighted average of 111.6 dB(A). Under the National Institute for Occupational Safety and Health (NIOSH) criterion applied by the authors, the measured equivalent level corresponded to a recommended unprotected exposure duration of approximately 0.54 minutes. This represents a criterion-based estimate, not an observed time to auditory injury [8].

These findings support including practice alongside competition when assessing exposure. However, small driver samples and incomplete monitoring limit generalisation; acoustic measurements alone do not establish hearing impairment in the monitored individuals [8,14].

4.3. Variation in Exposure Across Motorsport Environments

Vehicle category, circuit characteristics and measurement location influence the interpretation of motorsport noise data. Cockpit measurements and measurements in team or spectator areas represent different exposure situations. Bristol Motor Speedway was described as a particularly adverse acoustic setting because its compact, bowl-shaped configuration contributed to reflection and reverberation. Findings from this venue therefore require caution when extrapolated to other circuits [8].

For motorcyclists, experimental evidence highlights the importance of airflow and helmet orientation. In a wind-tunnel investigation using a commercial helmet mounted on a head model, the cavity beneath the helmet near the chin bar was identified as an important source of sound measured at the ears. Its contribution varied with airflow speed and helmet angle. These findings help explain the aerodynamic component of motorcycle noise, although the experiment did not quantify exposure during competitive racing or assess hearing outcomes in riders [9].

Additional evidence from karting broadens the range of vehicle types considered. Bevilacqua et al. compared competition and rental karts using laboratory and trackside measurements, alongside assessments of noise propagation into surrounding areas. The study identified differences between kart types and described changes in acoustic characteristics during acceleration and braking at bends. However, these environmental measurements did not quantify personal exposure at the driver's ear or assess hearing outcomes. They therefore complement the characterisation of motorsport noise without providing a directly comparable estimate of driver exposure [2].

Table 1 summarises selected studies of noise exposure in shooting sports and motorsport.

Table 1. Selected studies of noise exposure in shooting sports and motorsport

Study and context	Exposure assessment	Key numerical findings	Interpretation

Lwow et al. (2011), [12] Sport-shooting training	Training-pattern estimates of repeated firearm impulses	Approximately 150-200 shots per 90-minute individual session; 600-1350 impulses reaching a shooter during group training; approximately 200,000 impulses per annual macrocycle.	Scenario-specific estimates, including neighbouring shooters; not continuous individual seasonal dosimetry.
Lwow et al. (2012), [13] Sport shooting	Acoustic recordings during training and competition	C-weighted peak SPL: 138.2-165.2 dB. Recorded signal duration: 250-800 ms; high-power component: approximately 1-2 ms.	Peak level and signal duration describe different features; no hearing outcomes were measured.
Magara et al. (2016), [14] Car racing	Dosimetry in 10 drivers across five categories and four flag marshals	LAeq,8h: 112 dB(A) in both V8 Supercar drivers; 101-104 dB(A) in three Formula Ford drivers. Each monitored driver exceeded 140 dB(C) peak in at least one race.	Small samples; incomplete race monitoring. Cockpit measurements were not obtained beneath hearing protectors.
Kardous and Morata (2010), [8] Stock-car racing	Three circuits; 24 area and 26 personal measurements	One driver on a Bristol practice day: Leq 114.4 dB(A); eight-hour TWA 111.6 dB(A).	The driver result represents one monitored setting. Acoustic exposure was not linked to audiometric outcomes

Note: SPL, sound pressure level; LAeq,8h, A-weighted equivalent level normalised to eight hours; Leq, equivalent sound level over the monitored period; TWA, eight-hour time-weighted average. Peak levels, equivalent levels and impulse counts quantify different features of exposure and should not be used interchangeably to rank risk. None of these acoustic findings independently establishes hearing injury.

5. Auditory Outcomes in Shooting Athletes

5.1. Audiometric Findings

Sun and Mei examined 42 shooting athletes from Hubei Province, China, with a mean age of 17.57 ± 3.01 years. Air-conduction thresholds were measured bilaterally at nine frequencies between 0.128 and 8 kHz. Mean thresholds at 6 and 8 kHz were approximately 21-22 dB in the right ear and 23-26 dB in the left ear. These group-level results describe hearing sensitivity at individual frequencies but do not establish the prevalence of hearing loss among the athletes [25].

The between-ear comparisons showed a predominantly left-sided disadvantage in hearing sensitivity. In paired analyses, seven of the nine tested frequencies showed significantly higher thresholds on the left; no significant difference was detected at 0.128 or 0.256 kHz. At 8 kHz, the reported group means differed by 3.91 dB (25.81 dB on the left and 21.90 dB on the right), and six athletes had individual interaural differences exceeding 10 dB. The authors also identified asymmetry in participants classified as having normal hearing. Its occurrence in this

subgroup warrants further investigation, but the study provides no longitudinal evidence that it precedes or predicts hearing deterioration [25].

Evidence from other firearm users provides a useful comparison. Grinn and Le Prell studied 33 young firearm users and 37 non-users, all of whom met normal-hearing inclusion criteria. No statistically significant group differences were found in conventional or extended high-frequency audiometry, otoacoustic emissions, auditory brainstem responses, middle-ear muscle reflexes or speech-in-noise performance. Most firearm users-91%-reported wearing hearing protection always or almost always. These findings describe a selected, largely protected sample and cannot be used to estimate hearing-loss prevalence in competitive shooters or to establish the causal effectiveness of hearing protection [7].

5.2. Tinnitus and Subjective Auditory Symptoms

In a questionnaire study of 197 Polish sport shooters from 18 clubs, more than 20% reported hearing disturbances. The questionnaire covered tinnitus, perceived transient hearing deterioration and chronic hearing difficulties, alongside other otological complaints. The aggregate percentage therefore does not represent the prevalence of tinnitus alone. Likewise, reported transient hearing deterioration should not be equated with an audiometrically documented temporary threshold shift. Only 36% of women and 53% of men reported previous audiometric examinations during their sporting careers [11].

The relationship between subjective symptoms and physiological findings was examined by Bhatt et al. in 133 young adults with clinically normal hearing, including 56 with chronic tinnitus. Participants with tinnitus had elevated hearing thresholds without corresponding differences in distortion product otoacoustic emissions (DPOAEs), whereas firearm users showed elevated thresholds and lower DPOAEs than predicted from their thresholds. The analyses concerned overlapping subgroups rather than a cohort of competitive shooters. These results suggest that tinnitus and firearm-use history may be associated with different auditory profiles, but they neither establish tinnitus prevalence in shooting athletes nor demonstrate that firearm exposure caused the reported tinnitus [3].

5.3. Interpretation and Limitations of Current Athlete Evidence

The athlete studies provide complementary evidence, but their outcomes are not interchangeable. Sun and Mei measured hearing thresholds, whereas Lwow et al. assessed symptoms and hearing-related practices through a questionnaire. Neither study included an unexposed comparison group or longitudinal follow-up. Their findings therefore cannot establish whether the observed abnormalities developed during the athletes' shooting careers or progressed with continued exposure [11,25].

Further limitations concern the interpretation of the audiometric data. The Hubei study involved a small sample from one centre, predominantly comprising adolescents. The classification of hearing impairment was insufficiently specified, and bone-conduction testing was not reported. Individual noise exposure was not quantified, and the analyses did not establish the contributions of handedness, firearm type or hearing-protection use to interaural differences [25]. In the Polish survey, symptoms, protective practices and previous examinations were self-reported and thus susceptible to recall error [11].

Studies of broader firearm-user populations add physiological detail, but their applicability to competitive athletes remains limited. Both Grinn and Le Prell and Bhatt et al. selected participants with clinically normal hearing, and their findings should be interpreted within those recruitment criteria [3,7]. Prospective athlete studies combining baseline and follow-up audiological testing with individual exposure measurements would help determine the clinical significance and course of the reported auditory changes.

6. Auditory Outcomes in Motorsport Athletes

6.1. Audiometric Evidence in Motorcycle Racing

Evidence of hearing impairment in competitive motorcycle racing was reported by McCombe and Binnington in a study of 44 active Grand Prix riders. Participants underwent an otological examination and pure-tone audiometry, accompanied by an interview. Their median age was 28 years, and their median racing experience was 10 years. In 20 riders (45%), hearing thresholds were worse than the 95th percentile of age- and sex-matched reference data at more than one frequency [16].

Among these 20 riders, the authors reported a positive correlation between hearing deficit and racing experience ($r = 0.50$; $p < 0.05$). This association does not establish within-person deterioration over time or a causal effect of racing exposure. Years of competition provide only an indirect measure of acoustic exposure, and the absence of baseline audiograms or repeated assessments prevents conclusions about when the impairment developed or the contribution of racing relative to other exposures [16].

The study provides direct audiometric evidence from competitive riders, but its historical context limits generalisation. The reported 45% describes this particular sample and should not be presented as the current prevalence of hearing loss in Grand Prix racing. Establishing contemporary risk requires updated studies that relate hearing outcomes to individual exposure and protective practices.

6.2. The Exposure-Outcome Gap in Modern Motorsport

Research in car racing has combined noise measurements with questionnaire data, but the connection between exposure and measured hearing impairment remains insufficiently characterised. Magara et al. surveyed 125 participants, including 121 racing drivers and four flag marshals. Of the 55 respondents who reported previous hearing testing, nine recalled being informed that they had some degree of hearing loss. These findings concern self-reported results of earlier examinations, rather than audiometry performed within the study. The proportion affected among previously tested respondents therefore cannot be interpreted as hearing-loss prevalence across the sample or linked directly to the recorded noise levels [14].

More recent acoustic research does not necessarily address this limitation. Bevilacqua et al. investigated noise emissions from competition and rental karts through laboratory and trackside measurements, without assessing drivers' auditory function. Although such measurements characterise the racing environment, they cannot establish whether competitors experience temporary threshold shifts, persistent hearing impairment or tinnitus. The distinction is particularly relevant when interpreting environmental sound measurements, which do not by themselves represent an individual athlete's exposure at the ear under hearing protection [2].

Across the studies considered here, audiometric findings, recalled hearing-test results and acoustic measurements provide different types of evidence. Their methodological differences prevent direct comparisons of hearing-loss frequency between motorcycle and car racing and leave the relationship between cumulative exposure and auditory change unresolved [2,14,16]. Addressing this gap requires prospective studies that pair individual exposure monitoring with baseline and follow-up audiological assessments. Information on hearing-protection use, racing category and noise exposure outside sport would further support interpretation of changes observed during training and competition.

7. Audiological Assessment and Potential Surveillance

7.1. Pure-Tone Audiometry

Repeated pure-tone audiometry allows changes in an individual's hearing sensitivity to be assessed against an earlier examination. Its value in surveillance therefore depends on both the availability of baseline measurements and the confirmation of subsequent threshold changes. Themann et al. describe the NIOSH approach, in which a deterioration of at least 15 dB at an individual test frequency requires confirmation by repeat testing before it meets the recommended shift criterion. This occupational criterion illustrates how serial audiograms can be interpreted, but it should not be presented as either a sport-specific standard or sufficient evidence that a change was caused by noise [26].

For noise-exposed athletes, assessment should consider frequency-specific thresholds and differences between ears alongside exposure history and reported symptoms. Otoscopy, bone-conduction testing and middle-ear assessment may be needed to clarify abnormal findings. Conventional audiometry does not characterise all aspects of auditory function, however, and persistent difficulties despite normal thresholds may warrant further investigation. A clinical framework developed for combat-noise exposure supports integrating these findings with additional tests, although its application to routine athlete surveillance requires separate evaluation [4].

7.2. Extended High-Frequency Audiometry and Otoacoustic Emissions

Testing above 8 kHz extends the assessment to frequencies that conventional audiometry does not cover. The potential value of this additional range is illustrated by the retrospective analysis of 105 hunters reported by Tinazli and Tinazli. Using a threshold above 25 dB HL at any frequency within the respective test range, they identified abnormalities in 59.1% of participants at 4-8 kHz and in 78.1% at 10-18 kHz. Extended testing also identified abnormalities in 25 of the 43 hunters whose conventional high-frequency results were normal. The two assessments therefore provided partly different information. However, because participants were not followed over time, the findings do not demonstrate that extended high-frequency abnormalities precede or predict deterioration within the conventional range [27].

Otoacoustic emissions offer a physiological measure that complements the behavioural thresholds recorded during audiometry. In the analysis by Bhatt et al., distortion product otoacoustic emission (DPOAE) amplitudes in firearm users fell below the values estimated from their hearing thresholds, despite participants meeting the study's criteria for clinically normal hearing. This finding suggests that the relationship between hearing sensitivity and cochlear

emission strength may itself be informative [3]. Evidence is not uniform, however: Grinn and Le Prell found no statistically significant differences between firearm users and non-users in extended high-frequency thresholds or DPOAE measurements within their normal-hearing sample [7].
These findings support considering extended audiometry and emissions as supplementary measures rather than established stand-alone screening tools for athletes. Interpretation requires attention to age, measurement conditions and middle-ear status. Neither an abnormal result nor disagreement between tests independently establishes noise-induced cochlear damage [4,27].

7.3. Other Potential Tests

Speech-in-noise testing can help characterise functional complaints that are not explained by conventional thresholds. Auditory brainstem responses, frequency-following responses and middle-ear muscle reflex measures have also been investigated as potential indicators of auditory dysfunction in noise-exposed individuals. Their research applications should be distinguished from validated diagnostic criteria for individual athletes [1,7].
Grinn and Le Prell detected no significant differences in auditory brainstem responses, middle-ear muscle reflexes or Words-in-Noise performance between their firearm-user and control groups. Similarly, Ananthakrishnan et al., studying 10 hunters and 10 non-hunters with normal hearing, found no significant group differences in frequency-following responses or tonal middle-ear muscle reflexes; most perceptual outcomes were also similar. Small samples, participant selection and incomplete exposure characterisation limit the interpretation of these findings [1,7].
Additional testing may therefore be considered when symptoms and basic audiological findings are discordant, with test selection guided by the clinical question [4]. The firearm-user studies discussed here do not establish a validated battery for detecting cochlear synaptopathy in asymptomatic competitive athletes [1,7].

7.4. Frequency of Surveillance

An optimal interval between hearing assessments has not been established for shooting or motorsport athletes by the studies considered here. For sport shooters, Lwow et al. suggested a six-month interval during the initial year of training and yearly examinations thereafter. Their study did not compare alternative schedules or evaluate whether this approach improved the detection or prevention of hearing impairment. The proposed timing should therefore be identified as the authors' preventive recommendation rather than a validated surveillance schedule [11].
Occupational hearing-conservation programmes provide a framework for repeated assessment, but their schedules and criteria cannot automatically be treated as sport-specific standards [26]. Likewise, follow-up after acute acoustic trauma serves a different purpose from routine surveillance. Chordekar et al. describe early and repeated assessments after injury, with subsequent testing tailored to symptoms and previous findings; this clinical pathway should not be directly transferred to asymptomatic athletes [4].
A potential sport-specific programme could combine a baseline assessment with periodic review informed by exposure, symptoms and previous results. New auditory symptoms or an acute exposure event would require a separate clinical assessment rather than waiting for the next scheduled examination. Prospective studies are needed to determine which intervals and test combinations offer meaningful benefits in athletic populations.

8. Hearing Protection and Protective Practices

8.1. Use of Hearing Protection in Shooting Athletes

A survey of 197 Polish sport shooters from 18 clubs found that hearing protection was not universally used during either training or competition. Among women, 68% reported using protectors during training and 48% during competition; the corresponding proportions among men were 52% and 61%. These findings indicate gaps in protective practices in the surveyed population, although the questionnaire did not establish whether devices were worn throughout exposure or fitted correctly. Given the age of the study, these proportions should not be interpreted as current estimates of hearing-protector use among competitive shooters [11].
Reported use alone does not establish the protection achieved. Occupational research shows that individual attenuation can differ substantially from laboratory ratings. Fit testing can quantify attenuation for a particular fitting and help identify whether further instruction or a different protector is needed [26].

8.2. Barriers to Hearing-Protection Use

Comfort, communication and cost were among the reasons sport shooters gave for not wearing hearing protection. Participants surveyed by Lwow et al. reported discomfort with earmuffs and skin reactions associated with earplugs. Other concerns included difficulty communicating with coaches or fellow shooters, perceived

interference with concentration, and the expense of devices when costs were not covered by clubs. The authors did not quantify the frequency of each barrier, and the reported effects on communication and concentration were not assessed through performance testing [11].

These observations suggest that efforts to encourage hearing-protector use should address the practical concerns of athletes alongside their awareness of acoustic risk. Occupational research reviewed by Themann et al. similarly emphasises education tailored to users' attitudes, barriers and confidence in their ability to protect their hearing. This approach provides a rationale for incorporating comfort, affordability and communication requirements into preventive programmes for shooters, although its effectiveness in improving sustained use in competitive sport remains to be established [11,26].

8.3. Hearing Protection in Motorsport

Studies of Grand Prix motorcycle racers and Australian racing car drivers provide evidence of incomplete hearing-protection use in competitive motorsport [14,16]. Among 44 Grand Prix motorcycle racers, 17 (39%) reported regular earplug use, but only nine (20%) had used them for more than half of their racing careers [16]. In the survey by Magara et al., 121 of the 125 respondents were racing car drivers; among these drivers, 82 (67.8%) reported using hearing protection and 39 (32.2%) reported none [14]. Custom-moulded earplugs were the most frequently reported type among drivers. Use varied substantially across racing categories: all 26 V8 Supercar drivers reported protection, whereas 36 of 38 Saloon Car drivers reported none. However, the questionnaire results did not establish how consistently protection was worn during exposure[14] Differences in populations and reporting methods preclude interpreting these findings as evidence of improved uptake over time; they instead document gaps in protective practices within the respective samples [14,16].

8.4. Protection Versus Communication and Situational Awareness

The acoustic performance of hearing protectors provides only part of the information needed to assess their suitability for sport. Using an acoustic test fixture, Murphy et al. measured mean impulse peak insertion losses of approximately 20-38 dB across the tested devices and impulse levels, with some variation between individual devices and repeated fittings. Electronic devices were evaluated with their electronics switched off [23]. Outdoor measurements by Młyński and Kozłowski showed that all 11 tested level-dependent protectors reduced C-weighted peak and A-weighted maximum sound pressure levels below the adopted limits under the conditions examined [20]. In a separate indoor-range assessment, only four or six of ten protectors met the combined selection criteria, depending on the peak-level limit applied. This assessment used measured environmental noise and calculated attenuation, highlighting the importance of matching protection to the exposure scenario [21]. Neither study by Młyński and Kozłowski directly tested speech intelligibility or sound localisation.

Functional effects were examined by Fostick and Fink in 90 normal-hearing adults tested with earplugs, earmuffs or double protection. Hearing protectors increased localisation errors for a spoken word, pink noise and a recorded gunshot, with greater disruption under earmuff and double-protection conditions than with the tested earplugs. Although speech was included as a stimulus, the task assessed its location rather than its intelligibility. These findings identify a potential functional cost of protection, but they do not establish effects on communication or performance during sporting competition [5].

Some localisation difficulties may be reduced through training. In a randomised study of 50 young adults, three sessions of spatial-hearing training with feedback reduced front-back confusions while participants wore foam earplugs. Improvements in absolute localisation were also observed, although evidence of a training-specific effect was less clear for this measure. No significant reductions in the assessed measures of listening effort were detected [6]. These findings support further investigation of targeted training alongside protector selection, although the persistence of its benefits and its relevance to competitive athletes remain uncertain.

8.5. Engineering and Administrative Controls

Reducing noise at its source can complement individual hearing protection. Murphy et al. evaluated firearm suppressors and ammunition configurations using acoustic measurements around the firearm. Depending on the weapon and ammunition, suppressors lowered peak sound pressure levels at the shooter's ear position by 17-24 dB and eight-hour equivalent A-weighted levels by 9-21 dB. Greater reductions in sound power were obtained with low-velocity ammunition than with high-velocity ammunition, for which the projectile's ballistic shock wave contributed to the remaining noise. These reductions did not eliminate the potential hazard from cumulative exposure, and the authors continued to recommend hearing protection when firing suppressed weapons [22]. Equipment modifications may also increase exposure: Meinke et al. note that muzzle brakes used to reduce recoil can increase sound pressure levels at the shooter's ear by redirecting propellant gases [17].

Administrative measures address the duration and organisation of exposure. Murphy et al. identify limits on shooting time and the number of rounds fired during a training session as examples of such controls [22]. More broadly, the occupational framework reviewed by Themann et al. prioritises eliminating or reducing hazardous noise and combines engineering measures, exposure management and personal protection [26]. For shooting and motorsport, this framework could inform planning that limits unnecessary time in high-noise areas and uses exposure measurements to evaluate changes in equipment or training arrangements. Such applications require assessment within each sporting environment: the cited evidence does not establish a safe number of shots or a universally appropriate exposure schedule for athletes.

9. Sport-Specific Practical Considerations

9.1. Shooting Sports

In shooting sports, exposure includes shots fired by the athlete and by neighbouring competitors [12]. Hearing protection should therefore cover periods of gunfire during both training and competition, including intervals when the athlete is not actively shooting [11]. Selection should account for the firearm, ammunition and acoustic environment, since findings obtained for a particular protector and shooting configuration cannot establish its suitability across all settings [20,21]

Air rifles also warrant consideration. In outdoor measurements of ten commercially available pellet and BB rifles, eight exceeded the WHO (1999) reference of 120 dB peak SPL for children used in the study, as measured at the left-ear microphone position. However, the study assessed acoustic exposure rather than hearing outcomes and did not evaluate rifles with velocities between 350 and 600 feet per second, a range relevant to the three-position competitions discussed by the authors. These findings support assessing the specific equipment and shooting conditions, while avoiding direct extrapolation to lower-velocity competition rifles [10].

Communication needs should be addressed when selecting protection and organising training. Level-dependent devices may facilitate access to speech between shots, but their attenuation performance does not establish that speech intelligibility or sound localisation is preserved [5,20]. Source-control measures, including firearm suppressors where compatible with the discipline's equipment requirements, may further reduce exposure while remaining supplementary to hearing protection[22].

9.2. Motorsport

Protective practices in motorsport need to reflect the vehicle, racing category and duration of exposure. Measurements across different car-racing categories illustrate why a single hearing-protection specification may not suit all drivers. Assessment should also consider noise encountered before and after a race rather than treating race duration as the athlete's entire exposure [14].

For motorcycle riders, wearing a helmet should not be assumed to provide sufficient acoustic protection. McCombe's review describes limited low-frequency attenuation in helmets examined in earlier studies and discusses the challenges of retaining access to warning signals and radio communication. These observations support evaluating hearing protection together with the helmet, although they do not establish the performance of contemporary racing equipment [15]. Similarly, the use of ear moulds incorporating communication transducers, documented among racing car drivers, should prompt consideration of both noise attenuation and communication requirements; their reported use alone does not demonstrate adequate protection [14].

9.3. Athletes, Coaches and Officials

Implementing hearing protection requires support beyond the individual athlete. Reported discomfort, communication difficulties and unreimbursed equipment costs among sport shooters suggest that education alone may leave important barriers unresolved [11]. Clubs and organisers could address these barriers by facilitating access to suitable devices and practical instruction, while coaches reinforce their use during training. This approach is consistent with occupational evidence supporting education tailored to users' concerns and instruction in correct fitting, although its effect on sustained use in sport requires evaluation [26].

Coaches and officials also require assessment of their own exposure. Measurements at shooting-instructor positions and among flag marshals show that participation without firing a weapon or driving a vehicle does not exclude substantial noise exposure [14,21]. Preventive arrangements should therefore consider each role's location, time near active shooting or racing, and communication needs. In youth shooting, adults can additionally model protective behaviour from the earliest training sessions, an approach advocated by Lankford et al. rather than tested as a behavioural intervention in their acoustic study [10]. These considerations provide a basis for locally adapted prevention, rather than a uniform protocol validated across sporting disciplines.

10. Evidence Gaps and Directions for Future Research

10.1. Lack of Longitudinal Athlete Studies

The athlete studies discussed in this review provide limited evidence on how hearing changes over a sporting career. Sun and Mei assessed interaural hearing differences at a single examination, while McCombe and Binnington compared the hearing of active Grand Prix riders with population reference data. Neither study included measurements obtained before the athletes began their sporting careers or repeated follow-up examinations. Consequently, the observed asymmetry in shooters cannot be interpreted as a demonstrated precursor of hearing loss, and the association between hearing deficit and racing experience does not establish within-person deterioration over time [16,25].

Prospective cohorts beginning early in an athlete's career and continuing across multiple seasons would help establish the timing and progression of auditory changes. Repeated assessments should distinguish short-term post-exposure changes from persistent findings and account for age, previous noise exposure and relevant otological history. Following an appropriate comparison group over the same period would further strengthen interpretation. Such designs would provide a firmer basis for evaluating whether hearing changes are associated with continued sports participation and whether preventive measures alter their course.

10.2. Separation of Exposure and Hearing Outcomes

The studies considered here often characterise acoustic exposure and auditory outcomes separately. For example, Magara et al. combined noise measurements with questionnaire data on previous hearing examinations and reported hearing loss, but did not perform audiometry as part of the investigation [14]. Conversely, the audiometric studies of shooting athletes and Grand Prix motorcyclists did not link individual hearing findings to measured cumulative exposure across training and competition [16,25]. This separation limits the estimation of exposure-response relationships.

Future studies should pair individual exposure measurements with audiological assessments in the same athletes. Exposure records should include relevant training and competition periods, noise from nearby participants, and the duration and consistency of hearing-protector use. Such information would help distinguish the acoustic environment surrounding an athlete from the exposure actually reaching the ear.

10.3. Limited Contemporary Data in Motorsport

Within the literature reviewed, direct audiometric evidence from elite motorcycle racing relies heavily on the Grand Prix study published in 1994. McCombe's later review summarises earlier investigations rather than providing a new contemporary athlete cohort, while the racing-car study by Magara et al. contributes exposure and protective-practice data without new audiometric measurements [14,15,16]. These sources establish a reason for concern but cannot determine the current prevalence of hearing impairment in competitive motorsport.

Contemporary studies should distinguish motorcycle racing from car racing and document the vehicles, helmets, communication systems and hearing protectors in use. Recruitment across teams and racing categories would improve coverage of differing exposure conditions. Updated acoustic measurements should be accompanied by hearing assessments, allowing the relevance of historical findings to present-day competitors to be evaluated.

10.4. Need for Standardised Audiological Outcomes

Comparison across studies is complicated by differences in test frequencies, participant selection and definitions of abnormal hearing. Sun and Mei used a 20-dB boundary but provided limited detail on participant-level classification, whereas Tinazli and Tinazli defined abnormalities using thresholds above 25 dB HL at any frequency within specified conventional or extended high-frequency ranges. McCombe and Binnington instead evaluated hearing relative to age- and sex-matched population reference data [16,25,27]. These approaches address different questions and should not be treated as interchangeable estimates of hearing-loss prevalence.

A common reporting framework should specify the tested frequencies, ear-selection rules, definitions of asymmetry and hearing loss, and timing relative to recent noise exposure. Longitudinal studies should distinguish an elevated threshold at one examination from a confirmed change relative to baseline. Tinnitus and functional complaints also require explicit definitions and consistent reporting periods. Supplementary measures may broaden assessment, but findings from normal-hearing firearm users do not yet establish a validated diagnostic battery for subclinical injury in competitive athletes [1,7].

10.5. Need to Study Real-World Hearing Protector Performance

Acoustic test-fixture measurements and computational selection methods provide useful information about hearing-protector performance, but do not establish the attenuation achieved throughout a sporting session

[20,21,23]. Occupational research further demonstrates the importance of individual fitting, while laboratory studies identify effects on sound localisation and the potential for improvement through training [5,6,26]. Their practical significance during competition remains insufficiently characterised.
Field studies should examine fit, movement, compatibility with helmets or other equipment, and periods when protectors are removed. Acoustic protection should be evaluated alongside speech intelligibility, warning-signal detection and localisation, rather than assuming that one outcome represents the others. Longer follow-up would also help determine whether fitting instruction and spatial-hearing training produce lasting benefits and whether these benefits are retained under the demands of training and competition.

11. Limitations of the Review

This narrative review was based on targeted literature searches and should not be regarded as an exhaustive account of research on sport-related noise. Access to full texts constrained the material available for detailed assessment, potentially leaving relevant findings outside the synthesis. Differences in study populations, exposure measurements and definitions of auditory abnormality limited direct comparisons and prevented the reported proportions of hearing impairment from being interpreted as a common prevalence estimate. One Chinese-language study was assessed through an English translation, introducing an additional possibility of error in interpreting its methods and findings.
Evidence directly concerning competitive athletes was supplemented with research involving recreational firearm users, hunters, military personnel, workers and laboratory volunteers. Differences in exposure patterns, protective practices and participant selection restrict the applicability of these findings to sport. Acoustic measurements, calculated attenuation estimates and laboratory tests of auditory function also cannot establish the long-term clinical effectiveness of preventive measures in athletes.
Several influential motorsport studies describe historical equipment and practices, while some athlete studies involve small or narrowly selected samples. Cross-sectional designs and the absence of baseline measurements further limit conclusions about the development and progression of hearing impairment. The practical considerations presented in this review therefore draw on both direct sport evidence and cautious interpretation of related research. They provide a basis for prevention and further evaluation rather than validated sport-specific protocols.

12. Discussion

The evidence reviewed indicates that shooting sports and motorsport can expose participants to potentially hazardous noise, although the extent of associated hearing impairment in competitive athletes remains less clearly established. Acoustic studies document repeated firearm impulses and prolonged exposure during motor racing, whereas athlete studies provide more limited information on auditory outcomes [8,12,16,25]. These findings support attention to hearing health in sport, but do not provide a reliable estimate of the current prevalence of noise-induced hearing loss across disciplines.
The distinction between exposure and injury is central to interpreting this literature. High sound levels identify an acoustic hazard, but do not determine whether a particular athlete has sustained hearing damage. Conversely, an abnormal audiogram does not establish that sporting exposure was its sole cause. The findings in shooting athletes and Grand Prix motorcyclists therefore support considering sporting exposure within a broader assessment of hearing, otological history and other sources of noise[16,25].
Shooting and motorsport require different approaches to exposure assessment. In shooting, peak level, impulse characteristics and the contribution of neighbouring shooters all affect exposure. In motorsport, duration and variation across vehicles, sessions and track locations require particular consideration [8,12,13,14]. Prevention should reflect these differences, with measurements covering the relevant training and competition conditions.
Audiological surveillance offers a potential means of identifying changes over time, but the evidence reviewed does not establish an optimal test battery or examination interval for athletes. Extended high-frequency audiometry and otoacoustic emissions may provide information beyond conventional thresholds, although findings in hunters and firearm users are inconsistent [3,7,27]. These methods should consequently be interpreted as complementary assessments whose value depends on the clinical question. Methodological variation across the broader firearm literature, also identified by Sonstrom Malowski et al. [24] reinforces the need for clearly defined outcomes and consistent testing procedures.
Prevention requires attention to both the acoustic performance of hearing protectors and how they are used. Reports of incomplete use among shooters and racing participants identify a practical limitation that device attenuation alone cannot address[11,14,16]. Occupational evidence further shows that achieved attenuation depends on individual fit, while laboratory studies demonstrate that protectors can affect sound localisation [5,26]. These findings support evaluating fit, equipment compatibility and auditory task demands together. Training-related

reductions in front–back confusions suggest that some functional difficulties may be modifiable, although lasting benefits during competition have not been established [6].
Source reduction and exposure management should also be considered alongside personal protection. Suppressor measurements demonstrate reduced firearm noise under tested conditions without establishing that hearing protection becomes unnecessary [22]. Together with occupational hearing-conservation evidence, these findings support combining feasible noise reduction, appropriate protector selection and fitting, and audiological follow-up, with each component adapted to the sporting environment [26].

13. Conclusions

Shooting sports and motorsport can involve substantial noise exposure, but evidence linking individual exposure to long-term auditory outcomes in competitive athletes remains limited. Available findings justify including hearing health in athlete care without assuming a uniform risk across disciplines.
Prevention should combine assessment of the sporting acoustic environment, feasible exposure reduction and consistently worn, appropriately fitted hearing protection. Audiological follow-up may help identify changes over time, although athlete-specific testing schedules and the additional value of supplementary tests require further evaluation.
Prospective studies pairing individual exposure measurements with repeated audiological assessment are needed to clarify risk, evaluate protective practices and establish practical surveillance approaches. Contemporary motorsport cohorts and assessments of hearing-protector performance during actual training and competition are particularly important.

Disclosure

Author Contributions: Conceptualization, K.S., A.G., J.D., K.L., L.J., K.D., K.G., N.W., M.S. and S.K.; methodology, K.S., A.G., J.D., K.L., L.J., K.D., K.G., N.W., M.S. and S.K.; investigation, K.S., A.G., J.D., K.L., L.J., K.D., K.G., N.W., M.S. and S.K.; validation, K.S., A.G., J.D., K.L., L.J. and K.D.; writing-original draft preparation, K.S., A.G. and J.D.; writing-review and editing, K.S., A.G., J.D., K.L., L.J., K.D., K.G., N.W., M.S. and S.K.; visualization, K.S. and A.G.; project administration, K.S. All authors have read and agreed to the published version of the manuscript.
Funding: This research received no external funding.
Institutional Review Board Statement: Not applicable.
Informed Consent Statement: Not applicable.
Data Availability Statement: No new data were created or analysed in this study. Data sharing is not applicable to this article.
Conflicts of Interest: The authors declare no conflict of interest

Declaration of generative AI and AI-assisted technologies in the writing process: OpenAI

ChatGPT was used solely for editorial purposes, including grammatical correction, language refinement, reference verification, and manuscript formatting. All AI-assisted content was subsequently reviewed and revised by the authors, who take full responsibility for the accuracy, integrity, and final content of the manuscript.

References

1. Ananthakrishnan S, McElree C, Martin L. Physiological and perceptual auditory consequences of hunting-related recreational firearm noise exposure in young adults with normal hearing sensitivity. Noise Health. 2023 Jan;25(116):8–35. https://doi.org/10.4103/nah.nah_53_22

2. Bevilacqua A, Iannace G, Gomez-Agustina L, Trematerra A. Racing in Kart Dromes: Laboratory and Site Assessment of Noise Levels from Competition and Rental Karts. Acoustics. 2024 Dec 17;6(4):1180–92. https://doi.org/10.3390/acoustics6040064

3. Bhatt IS, Lichtenhan J, Tyler R, Goodman S. Influence of tinnitus, lifetime noise exposure, and firearm use on hearing thresholds, distortion product otoacoustic emissions, and their relative metric. J Acoust Soc Am. 2023 Jul 1;154(1):418–32. https://doi.org/10.1121/10.0019880

4. Chordekar S, Brand D, Leiderman Badash OS, Adelman C, Fraenkel R, Horev N, Ben Horin A, Fink N. Recommended Audiological Test Battery Following Combat Noise Exposure: A Clinical Approach. J Speech Lang Hear Res. 2026 Jan 8;69(1):286–306. https://doi.org/10.1044/2025_JSLHR-25-00284

5. Fostick L, Fink N. Situational Awareness: The Effect of Stimulus Type and Hearing Protection on Sound Localization. Sensors. 2021 Oct 24;21(21):7044. https://doi.org/10.3390/s21217044

6. Golob EJ, Nelson JT, Piedra ET, Adams JK, Esquivel CR, Spear SA, Mock JR. Brief training can reduce spatial hearing deficits when wearing hearing protection. J Neurophysiol. 2026 May 1;135(5):1159–74. https://doi.org/10.1152/jn.00107.2025

7. Grinn SK, Le Prell CG. Evaluation of hidden hearing loss in normal-hearing firearm users. Front Neurosci. 2022 Oct 26;16:1005148. https://doi.org/10.3389/fnins.2022.1005148

8. Kardous CA, Morata TC. Occupational and recreational noise exposures at stock car racing circuits: An exploratory survey of three professional race tracks. Noise Control Eng J. 2010;58(1):54–61. https://doi.org/10.3397/1.3270506

9. Kennedy J, Adetifa O, Carley M, Holt N, Walker I. Aeroacoustic sources of motorcycle helmet noise. J Acoust Soc Am. 2011 Sep 1;130(3):1164–72. https://doi.org/10.1121/1.3621097

10. Lankford JE, Meinke DK, Flamme GA, Finan DS, Stewart M, Tasko S, Murphy WJ. Auditory risk of air rifles. Int J Audiol. 2016 Feb 12;55(Suppl 1):S51–8. https://doi.org/10.3109/14992027.2015.1131851

11. Lwow F, Jóźków P, Gawron W, Mędraś M. Prevention of Hearing Impairment in Sport Shooters. Med Sport. 2007 Dec 1;11(4):108–12. https://doi.org/10.2478/v10036-007-0021-3

12. Lwow F, Jóźków P, Mędraś M. Occupational Exposure to Impulse Noise Associated With Shooting. Int J Occup Saf Ergon. 2011 Jan;17(1):69–77. https://doi.org/10.1080/10803548.2011.11076873

13. Lwow F, Jóźków P, Mędraś M. Evaluation of the time and the time/frequency structure of handgun noise as a basis for hearing loss prevention in sport shooters. Fizjoterapia. 2012;20(1):3–9. https://doi.org/10.2478/v10109-012-0001-6

14. Magara K, Jansz J, Bertolattia D, Dhaliwal S. Noise exposure assessment for racing car drivers. World Safety Journal. 2016;XXV(1):30–45.

15. McCombe AW. Hearing Loss in Motorcyclists: Occupational and Medicolegal Aspects. J R Soc Med. 2003 Jan;96(1):7–9. https://doi.org/10.1177/014107680309600103

16. McCombe AW, Binnington J. Hearing loss in Grand Prix motorcyclists: occupational hazard or sports injury? Br J Sports Med. 1994 Mar;28(1):35–7. https://doi.org/10.1136/bjsm.28.1.35

17. Meinke DK, Finan DS, Flamme GA, Murphy WJ, Stewart M, Lankford JE, Tasko S. Prevention of Noise-Induced Hearing Loss from Recreational Firearms. Semin Hear. 2017 Nov;38(4):267–81. https://doi.org/10.1055/s-0037-1606323

18. Meinke DK, Finan DS, Soendergaard J, Flamme GA, Murphy WJ, Lankford JE, Stewart M. Impulse noise generated by starter pistols. Int J Audiol. 2013 Feb;52(Suppl 1):S9–19. https://doi.org/10.3109/14992027.2012.745650

19. Meinke DK, Murphy WJ, Finan DS, Lankford JE, Flamme GA, Stewart M, Soendergaard J, Jerome TW. Auditory risk estimates for youth target shooting. Int J Audiol. 2014 Mar;53(Suppl 2):S16–25. https://doi.org/10.3109/14992027.2013.865845

20. Młyński R, Kozłowski E. Noise reduction at the shooting range by means of level-dependent hearing protectors. Med Pr. 2019 Jun 14;70(3):265–73. https://doi.org/10.13075/mp.5893.00730

21. Młyński R, Kozłowski E. Selection of Level-Dependent Hearing Protectors for Use in An Indoor Shooting Range. Int J Environ Res Public Health. 2019 Jun 27;16(13):2266. https://doi.org/10.3390/ijerph16132266

22. Murphy WJ, Flamme GA, Campbell AR, Zechmann EL, Tasko SM, Lankford JE, Meinke DK, Finan DS, Stewart M. The reduction of gunshot noise and auditory risk through the use of firearm suppressors and low-velocity ammunition. Int J Audiol. 2018 Jan 26;57(Suppl 1):S28–41. https://doi.org/10.1080/14992027.2017.1407459

23. Murphy WJ, Flamme GA, Meinke DK, Sondergaard J, Finan DS, Lankford JE, Khan A, Vernon J, Stewart M. Measurement of impulse peak insertion loss for four hearing protection devices in field conditions. Int J Audiol. 2012 Feb;51(Suppl 1):S31–42. https://doi.org/10.3109/14992027.2011.630330

24. Sonstrom Malowski K, Gollihugh LH, Malyuk H, Le Prell CG. Auditory changes following firearm noise exposure, a review. J Acoust Soc Am. 2022 Mar 1;151(3):1769–1791. https://doi.org/10.1121/10.0009675

25. Sun YQ, Mei HX. A Study on the Asymmetric Characteristics of Binaural Hearing Ability of Shooting Athletes in Hubei Province. Leis Sports Health. 2024;4(1):48–53. https://doi.org/10.35534/lsh.0401009

26. Themann CL, Masterson EA, Peterson JS, Murphy WJ. Preventing Occupational Hearing Loss: 50 Years of Research and Recommendations from the National Institute for Occupational Safety and Health. Semin Hear. 2023 Nov;44(4):351–93. https://doi.org/10.1055/s-0043-1769499

27. Tinazli R, Tinazli M. Detection and Grading of Early-Stage Cochlear Damage in Land Hunters by Comparison of Extended High-Frequency Audiograms with Conventional High-Frequency Audiograms. J Audiol Otol. 2022 Apr 10;26(2):83–9. https://doi.org/10.7874/jao.2021.00605