

Research progress on insertion loss measurement and effective sound pressure level prediction models of hearing protectors under high-intensity impulse noise

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Abstract: Impulse noise, characterized by extremely high peak levels, rapid rise times, and very short durations, poses a far greater risk to hearing than continuous noise of comparable energy. Conventional assessment methods developed for steady-state exposures often underestimate the hazard of such impulses, creating a need for models and measurement approaches that accurately predict effective sound pressure levels behind hearing protectors. This review synthesizes current knowledge on impulse noise characteristics, laboratory and field measurement techniques, and prediction models designed for hearing protector evaluation. Evidence indicates that energy-equivalent metrics such as A-weighted equivalent levels are insufficient for impulse conditions. Parametric models that include peak level and duration, frequency-dependent approaches that emphasize spectral distribution and waveform statistics, and biophysical algorithms that simulate auditory responses offer progressively greater predictive accuracy. Recent hybrid frameworks, supported by computational modelling, machine learning, and wearable dosimetry, represent promising directions for integrating laboratory precision with field relevance. When applied to hearing protectors, prediction models reveal both their strengths and limitations. Laboratory studies confirm substantial attenuation under controlled conditions, but nonlinear protector behaviour and fit variability reduce reliability in real-world use. Field data demonstrate that cumulative and waveform-sensitive metrics align more closely with observed auditory outcomes than peak-only criteria. The findings underscore the importance of developing harmonized standards and adopting advanced prediction frameworks. Such progress is essential for improving hearing conservation strategies in military, industrial, and other high-risk environments.

Keywords: auditory hazard; hearing protectors; impulse noise; insertion loss; prediction models

1. Introduction

1.1. Context: impulse noise and its hazards

Impulse noise has long been recognized as one of the most damaging forms of acoustic exposure [1]. It refers to sudden and brief acoustic events generated by sources such as firearms, blasts, hammer strikes, and industrial impacts [2]. Unlike continuous noise, which is typically averaged over time, impulse noise is defined by its extremely high peak sound pressure levels [3], short duration, and rapid rise times that may be measured in microseconds [2]. These characteristics combine to create acoustic conditions that can overwhelm the auditory system within a fraction of a second [1].

Reports from military training ranges, industrial workshops, and law enforcement environments consistently show that impulse noise exposure is associated with a greater incidence of permanent hearing loss compared with exposure to steady-state noise of equivalent energy [1].

1.2. Limitations of conventional assessment

Traditional metrics such as the Noise Reduction Rating (NRR) and the Single Number Rating (SNR) were originally developed primarily for continuous broadband noise [3]. These indices provide an average attenuation value that is useful for regulatory purposes but often fail to accurately represent the complex behaviour of hearing protectors under impulse conditions [4]. Impulse noise involves rapid pressure transitions and nonlinear acoustic effects; as a result, laboratory values derived from continuous test signals can overestimate the protection available in practical scenarios [5]. For instance, a hearing protector with a high rating for continuous noise may still allow harmful peak levels to be transmitted during impulsive exposures, such as gunshots or blasts [6]. This mismatch has been a persistent issue for both occupational safety and military hearing conservation programs [5].

Early studies attempted to apply continuous noise dose models to impulsive sounds by calculating an energy equivalent level [7]. While this approach is convenient, it assumes that hearing damage is primarily related to total acoustic energy and neglects factors such as peak amplitude, rise time, and waveform shape [8]. Accumulated evidence indicates that short, intense impulses can cause more severe damage than predicted by energy equivalence [9]. Consequently, agencies such as the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA), and the United States Department of Defense have adopted stricter peak sound pressure criteria for impulse exposures [10]. However, these criteria remain subjects of debate, and the lack of international harmonization continues to create uncertainty in both research and practice [11].

1.3. Rationale for studying hearing protectors under impulse noise

Hearing protectors remain the primary line of defense against acoustic injury in environments where impulse noise cannot be eliminated [12]. Devices such as earplugs, earmuffs, and combined double protection are widely used in both industrial and military settings [6]. Yet their actual effectiveness in real impulse scenarios remains difficult to quantify [13]. Standard test methods such as Real Ear Attenuation at Threshold (REAT), Microphone in Real Ear (MIRE), and Acoustic Test Fixtures provide valuable information under controlled conditions but exhibit limitations when extended to impulse scenarios [14]. REAT is subjective and involves ethical concerns when extreme noise levels are tested with human participants [15]. MIRE techniques are more objective; however, they may be limited by the dynamic range of probe microphones [16]. Acoustic Test Fixtures provide repeatability but do not perfectly reproduce human anatomy or ear canal acoustics [17].

To overcome these issues, the Impulse Peak Insertion Loss (IPIL) procedure has been standardized in ANSI S12.42 [18]. This method uses acoustic shock tubes to

generate controlled impulse waveforms with specified peak levels and durations [6]. It has become a reference for evaluating protector performance under impulse conditions and has highlighted the nonlinear attenuation properties that occur at very high intensities [19]. Such nonlinear effects include saturation, resonance, and leakage phenomena that are not captured by continuous noise tests [20]. Understanding these behaviors is crucial for predicting the real protection provided by hearing protectors during exposure to hazardous impulses [21].

1.4. Modelling approaches and emerging trends

Parallel to experimental methods, modelling approaches have been developed to predict the effective sound pressure level reaching the ear during impulse exposure. Energy-based models approximate impulse noise as equivalent continuous exposures, while parameter-based models explicitly consider peak level, rise time, and duration as determinants of injury risk [5]. More recently, computational methods such as finite element modelling, bioacoustics simulation, and machine learning have been applied to explore the complex interactions between impulse waveforms, hearing protector materials, and the ear canal [4]. These models aim not only to improve risk assessment but also to guide the design of next-generation hearing protectors optimized for impulse environments [22].

Emerging trends suggest a shift from reliance on continuous noise metrics toward impulse-specific frameworks that integrate both experimental and computational evidence [23]. At the same time, limitations remain. Variability between individuals, inconsistencies across protector types, and the absence of harmonized international standards continue to hinder accurate prediction and reliable regulation [24]. Ethical concerns restrict direct human testing, which means that many models cannot yet be fully validated [25]. These gaps underscore the importance of comprehensive reviews that consolidate available knowledge and highlight priorities for future research [15].

1.5. Aim and scope of the review

This review addresses the urgent need for synthesis in the field of hearing protection under high intensity impulse noise. Its objectives are fourfold. First, it describes the acoustic and physiological characteristics of impulse noise and the mechanisms through which it damages the auditory system. Second, it critically evaluates measurement methods used to determine the insertion loss of hearing protectors in impulse environments. Third, it summarizes prediction models developed to estimate effective sound pressure levels, with emphasis on both traditional and emerging approaches. Fourth, it discusses the limitations of current practices and identifies future directions for research, standardization, and technology development.

By pursuing these objectives, the review provides a structured resource for researchers, engineers, and policymakers concerned with hearing conservation. It emphasizes that conventional approaches designed for continuous noise are insufficient for impulses and that progress requires both refined measurement techniques and advanced predictive models. Ultimately, this work seeks to support the development of international standards and innovative protective strategies capable of addressing the

unique risks posed by high intensity impulse noise.

2. Characteristics of high intensity impulse noise

2.1. Acoustic properties

Impulse noise is defined by its extremely short duration, rapid onset, and very high peak sound pressure levels [26]. In typical field or laboratory recordings, impulses exhibit rises times shorter than one hundred microseconds, followed by rapid decay [27]. Peak sound pressures often range from 134 to 170 decibels, far exceeding the levels normally encountered in industrial environments dominated by continuous noise [1]. Due to this rapid rise, the waveform presents a steep pressure gradient that imposes sudden mechanical stress on the auditory system [28].

Duration is another important descriptor; the most common measures are A duration, which is the time from the onset to the initial return to baseline, and B duration, which includes the secondary oscillations until the waveform stabilizes [29]. These parameters allow classification of impulses that may differ in shape even when they share similar peak levels [30]. Impulse noise also differs from continuous noise in its spectral distribution. Continuous noise often has stable frequency content, while impulses typically contain broad frequency components with strong high-frequency energy that penetrates deeply into the cochlea [31]. This combination of high peak pressure, fast rise time, and broad frequency content explains why impulses are uniquely hazardous compared to continuous sound of equal energy [32].

2.2. Physiological impact

The effects of impulse noise on the auditory system are both immediate and cumulative [33]. Mechanical injury can occur when intense pressure waves physically damage structures of the ear, which may include rupture of the tympanic membrane, disarticulation of the ossicles, or shearing of cochlear hair cells. Because the energy is delivered in a fraction of a second, the ear has no opportunity to adapt or engage protective reflexes [34].

Metabolic injury represents another pathway of damage; intense stimulation triggers excessive neurotransmitter release and oxidative stress within cochlear cells, leading to metabolic exhaustion and eventual cell death [35]. Even when no mechanical rupture occurs, repeated impulses can cause irreversible degeneration of sensory structures [36]. The clinical outcomes include temporary threshold shifts after short exposure and permanent threshold shifts after repeated or severe exposure [6].

Epidemiological studies confirm that impulse noise contributes significantly to occupational hearing loss [37]. Military standards such as MIL STD 1474E and occupational guidelines from OSHA recognize these risks by setting strict peak pressure limits, often around 140 decibels [38]. However, unlike continuous noise, the dose-response relationship for impulse exposure remains poorly defined [39]. Thresholds for safe exposure vary across studies, and differences in waveform shape, duration, and repetition rate complicate risk assessment [40]. This uncertainty emphasizes the need for further experimental and modelling research [41].

2.3. Challenges in evaluation

Accurate evaluation of impulse noise presents both technical and ethical challenges. In the laboratory, researchers seek to replicate impulse events in a controlled manner, but real-world sources such as firearms and explosions are hazardous and inherently variable [42]. To address this, acoustic shock tubes and mechanical impactors are widely used. These systems can generate reproducible waveforms with specified peak levels and durations, making them suitable for standardized testing [40]. Nonetheless, the fidelity of these simulations in capturing complex battlefield or industrial conditions remains limited. For example, reflections, reverberation, and multiple overlapping impulses in real settings are challenging to reproduce with simple shock tube designs [43].

Ethical considerations further constrain research. Direct testing with human subjects at dangerous levels is unacceptable, meaning that much of the available evidence comes from mannequin-based tests, animal models, or retrospective analyses of exposed populations [44]. Each approach has limitations: mannequins may not accurately replicate human anatomy, animal results are not always transferable, and epidemiological data are influenced by uncontrolled variables [45]. As a result, there remains a lack of universally accepted criteria for defining safe exposure limits or evaluating hearing protector effectiveness against impulses [46].

Another challenge is measurement instrumentation. Capturing impulses with rise times below one hundred microseconds requires sensors with very high bandwidth and minimal distortion [26]. Standard microphones may underreport peak levels or smear waveform details, leading to inaccurate assessments of both noise characteristics and protector performance [47]. Advances in high-speed microphones and data acquisition systems have improved fidelity, but differences across laboratories continue to hinder international comparability [48].

3. Methods

3.1. Review design

This study was conducted as a narrative review focusing on prediction models and measurement approaches for effective sound pressure levels of hearing protectors under impulse noise. The design was chosen to synthesize theoretical frameworks, experimental methods, and applied studies from both military and industrial contexts. Unlike systematic reviews that follow strict protocols for study inclusion, this narrative approach allowed the integration of diverse evidence, including standards, technical reports, and computational studies, alongside peer-reviewed journal articles.

3.2. Eligibility criteria

The review focused on studies that investigated impulse noise, defined as acoustic events with high peak pressure, rapid rise time, and short duration. Eligible publications included experimental measurements of insertion loss, computational and biophysical models, and field studies linking impulse exposure to auditory outcomes. Studies limited to continuous noise, reviews unrelated to impulse-specific hazards, and papers without methodological relevance to prediction models were excluded. Both laboratory and

field investigations were considered, as well as standards and technical memoranda relevant to hearing protector evaluation.

3.3. Information sources and search strategy

Relevant literature was identified through database searches in Scopus, Web of Science, PubMed, and IEEE Xplore. Keywords and combinations included “impulse noise,” “hearing protector,” “insertion loss,” “IPIL,” “prediction model,” “auditory hazard,” and “effective sound pressure level.” Additional references were identified through manual screening of bibliographies, technical standards (e.g., ISO, EN, and MIL specifications), and institutional reports. No restrictions were placed on geographical origin, but priority was given to work published within the past three decades to reflect advances in measurement and modeling techniques.

3.4. Study selection and data extraction

All identified records were screened for relevance based on title and abstract. Full texts were reviewed to confirm eligibility against the predefined criteria. Extracted data included study objectives, methods of impulse noise generation and measurement, type of hearing protector tested, description of prediction models, and reported outcomes such as insertion loss or estimated auditory risk. Technical details of standards and computational approaches were also summarized where applicable.

3.5. Data synthesis

Given the heterogeneity of the included studies, results were synthesized narratively rather than statistically. Evidence was organized into thematic categories corresponding to the review framework: (1) characteristics of impulse noise, (2) measurement methods for insertion loss, and (3) prediction models of effective sound pressure levels. Comparative evaluation emphasized methodological strengths and weaknesses, applicability across contexts, and gaps requiring future research. The synthesis aimed to provide a coherent overview of the field and to highlight pathways toward improved prediction and harmonized standards.

4. Prediction models for effective sound pressure levels

4.1. Categories of models

The prediction of effective sound pressure levels under impulse noise has developed through several generations of models. The earliest approaches relied on energy-equivalent metrics, including the A-weighted equivalent level (LAeq) and sound exposure level (SEL) [36]. These models assume that the primary determinant of auditory hazard is cumulative acoustic energy, irrespective of waveform shape or rise time [49]. While simple and widely used, energy-based descriptors have been shown to underestimate the hazard of impulses with extremely steep rise times or high peak pressures, even when their total energy is modest [50].

In response, parametric models were proposed that incorporate waveform-specific features. The Pfander criterion integrates unweighted peak pressure with C-duration,

defined as the period the signal remains within 10 dB of its maximum value. Similarly, the LIAeq metric modifies LAeq by including adjustments for impulse duration, yielding stronger correlations with temporary threshold shift data in both laboratory and field settings [51].

As research progressed, it became clear that frequency content also plays a significant role. Frequency-dependent models emerged, emphasizing the disproportionate contribution of mid-to-high frequency energy (1–6 kHz) to auditory damage. Metrics such as kurtosis-adjusted LAeq, which incorporate statistical properties of waveform distributions, have demonstrated superior predictive validity in complex noise environments [52–54]. These models are particularly useful for evaluating noise in mixed industrial environments where impulses are superimposed on background continuous sound [55].

The most physiologically oriented class is represented by biophysical models, with the Auditory Hazard Assessment Algorithm for Humans (AHAH) being the best known. AHAH simulates middle ear transmission and basilar membrane motion to estimate auditory risk in auditory risk units [53,56]. Although AHAH has been incorporated into U.S. military standards (MIL-STD-1474E), its predictions often diverge from epidemiological findings, particularly under repeated exposure scenarios [51,52].

Finally, recent advances point toward emerging hybrid models that combine multiple elements: physiological simulation, energy descriptors, statistical indices, and machine learning. These frameworks are increasingly supported by wearable dosimetry, which provides real-time, individualized exposure data for model calibration [54].

The conceptual progression of these model types is summarized in **Figure 1**. The framework shows the evolution from energy-based indices toward hybrid approaches, with standards (ISO 4869/EN 458, NATO guidance, MIL-STD-1474E) linked to corresponding categories and applications mapped to each domain.

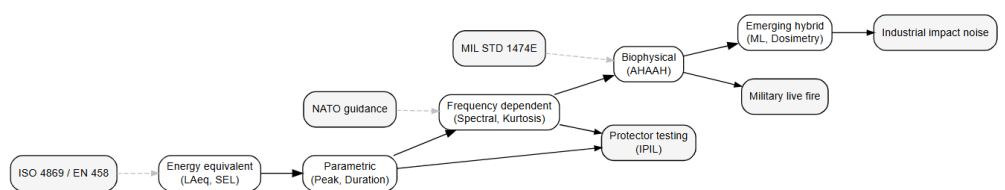


Figure 1. Conceptual framework of prediction models for effective sound pressure levels under impulse noise exposure.

Note: Models evolve from simple energy-based descriptors toward hybrid approaches, with standards and applications linked to each category.

4.2. Applications in protector assessment

Prediction models are indispensable for translating laboratory metrics into practical evaluations of hearing protector performance under impulse conditions.

For earplugs, attenuation often demonstrates nonlinear behaviour. Laboratory studies using acoustic shock tubes show that at peak levels above 160 dB, attenuation can flatten or even decline, suggesting saturation effects [57]. In the U.S. Navy study of the 3M™ E-A-R™ Classic™ earplug, mean impulse peak insertion loss (IPIL) values were 58.7 dB at 160 dBP and 57.5 dB at 170 dBP, sufficient to reduce exposures below 140 dBP up to impulses of 180 dBP. However, trial-to-trial variability exceeded 6 dB,

highlighting the influence of fit and insertion technique [57].

For earmuffs, design parameters such as cup mass, cushion compliance, and seal integrity are critical. Computational acoustic models confirm that small changes in geometry or fit can substantially alter attenuation in the impulse domain [52]. Double protection systems combining earplugs and earmuffs have been shown to provide substantial additional attenuation, but results are not strictly additive due to nonlinear protector interactions [52].

Field validation further emphasizes the importance of predictive models. Kulinski et al. [54] monitored over 200 service members during live-fire and breaching exercises using in-ear dosimetry. Logistic regression revealed that cumulative LAeq,8h was a stronger predictor of temporary threshold shift than peak or AHAH risk units, while kurtosis-adjusted LAeq produced the closest match to observed shifts. These findings demonstrate the superiority of statistical and frequency-sensitive models over traditional peak-based metrics in predicting field outcomes.

In industrial environments, model-informed protector selection is also critical. Kozłowski and Młyński [23] showed that protector ratings varied by as much as 9 dB depending on whether selection was based on octave-band, HML, or SNR methods, demonstrating that ignoring frequency distribution leads to systematic misestimation. This supports the application of frequency-dependent and kurtosis-based models for industrial impact noise [58].

Models are not limited to protectors themselves but extend to engineered noise controls. Tasko et al. [59] applied ANSI/ASA S12.42 IPIL methods to firearm suppressors, demonstrating that the same prediction framework used for protectors can be adapted to evaluate environmental controls, broadening its applicability.

4.3. Limitations of existing models

Despite significant progress, several limitations constrain the predictive accuracy of current approaches.

Individual variability is a persistent issue. Even under tightly controlled exposures, subjects vary widely in susceptibility to temporary and permanent threshold shifts due to factors such as age, genetics, and prior exposure history [54]. Models based on population averages cannot easily account for this heterogeneity.

Nonlinear protector behaviour presents another limitation. Koliás et al. [57] showed that foam earplug attenuation curves flattened at peaks beyond 160 dB, while other protectors demonstrated resonance-related leakage at particular frequencies. Current models often assume linear protector behaviour, failing to capture such effects [52].

The absence of harmonized standards complicates global application [60]. U.S. military doctrine integrates various standards, particularly those aligned with ISO frameworks and peak pressure limits for operational efficiency [61]. European agencies utilize ISO 50001 for energy management, which supports energy integration initiatives [62]. NATO guidance emphasizes frequency-dependent descriptors, underlining the diverse frameworks adopted across regions [60].

These differing approaches hinder international comparability and effective cross-sector communication, highlighting the need for a unified framework [63].

Measurement artifacts also undermine predictions. Weger [51] demonstrated that sampling rate, microphone bandwidth, and quantization significantly affected Pfander and LIAeq values, while kurtosis-adjusted LAeq and AHAAH were more robust. Similarly, Młyński and Kozłowski [58] showed that conventional sound level meters often saturate under impulses, producing underestimated peak levels and misleading protector evaluations.

Finally, there is a lab-to-field gap. The Noise Control 2022 monograph emphasized that ISO-based evaluations are typically performed under idealized conditions, neglecting reverberant or mixed impulse-continuous environments found in workplaces. This disconnect reduces the real-world relevance of laboratory-derived protector ratings.

4.4. Emerging approaches

Future progress will rely on integrating diverse data sources and methods into hybrid predictive frameworks.

Finite-element simulations of the ear canal and protector interface are increasingly used to model nonlinear acoustic behaviour, including leakage and variability due to anatomical differences [53]. These simulations allow researchers to explore conditions that cannot be ethically tested in humans.

Machine learning methods offer the potential to combine multiple descriptors, including LAeq, kurtosis, spectral balance, and protector type, into predictive models trained on large datasets. Preliminary studies suggest these approaches can outperform single-metric predictors [51].

Wearable dosimetry is transforming field research. Devices capable of capturing in-ear impulse exposures in real time provide personalized exposure profiles. Kulinski et al. [54] used such devices to link thousands of impulse events to individual auditory outcomes, paving the way for adaptive conservation strategies that respond dynamically to exposure.

Finally, the adaptability of IPIL methodology beyond protectors, as shown by Tasko et al. [59] with firearm suppressors, demonstrates the versatility of standardized test frameworks. By extending predictive approaches to engineered noise controls, hybrid models can unify evaluation of personal and environmental protective strategies. To provide a concise overview of the key prediction model categories and their respective strengths and limitations, **Table 1** summarizes the main characteristics discussed in Sections 4.1 to 4.4.

Table 1. Comparison of the main model categories, their parameters, advantages, limitations, and key references.

Model type	Key parameters	Advantages	Limitations	Example references
Energy-equivalent (LAeq, SEL)	Total energy	Simple, regulatory basis	Fails for short rise time impulses	Smootenburg [50]
Parametric (Pfander, LIAeq)	Peak, duration, rise time	Improved correlation with TTS	Sensitive to measurement settings	Weger [51]
Frequency-dependent	Spectrum, kurtosis	Captures high-frequency damage potential	Requires detailed waveform data	Hohmann, [52]; Kozłowski and Młyński [23]

Table 1. *Cont.*

Model type	Key parameters	Advantages	Limitations	Example references
Biophysical (AHA AH)	Basilar membrane displacement	Physiological basis	Misalignment with field data	Davis and Clavier [53]; Hohmann [52]
Emerging hybrid	Energy + spectral + ML	Adaptive, individualized	Needs large datasets	Kulinski [54]; Tasko [59]

Note: Abbreviations: LAeq, A-weighted equivalent continuous sound pressure level; SEL, sound exposure level; TTS, temporary threshold shift; AHA AH, Auditory Hazard Assessment Algorithm for Humans; ML, machine learning.

5. Discussion

5.1. Overview of model evolution

The study of prediction models for effective sound pressure levels in impulse noise has shown a clear evolution [64]. Initial reliance on energy-equivalent metrics was sufficient for continuous noise but often fell short for impulse noise characterized by rapid rise times and high peaks [65]. Subsequent parametric models introduced temporal descriptors, while frequency-dependent models emphasized spectral contributions [66]. Biophysical approaches, such as auditory hazard algorithms, have added physiological realism [67]. Furthermore, recent hybrid models combine computational, statistical, and physiological features [36]. This progression underscores the recognition that no single descriptor adequately predicts auditory risk across all impulse conditions [68].

5.2. Implications for hearing protector assessment

When applied to hearing protectors, prediction models provide both valuable insights and notable challenges [69]. Laboratory studies indicate that properly fitted protectors can reduce exposure to safe levels even under extreme impulse sounds, but variability in fit introduces significant uncertainty [70]. Nonlinear protector behaviour complicates modelling, particularly regarding attenuation flattening at high sound levels [69].

Field investigations suggest that cumulative and waveform-sensitive descriptors align more closely with auditory outcomes than peak-only measures [71]. This underscores the importance of models that incorporate statistical and spectral information when assessing protector performance [72]. In industrial environments, protector selection methods that do not account for frequency distribution may lead to inaccuracies in protection estimation [70]. These findings emphasize the necessity of advanced models for effective risk assessments in both military and industrial contexts [73].

5.3. Challenges and limitations

Despite progress, several barriers limit the reliability of current prediction models [74]. Individual susceptibility varies widely, influenced by age, genetics, and prior exposure. Models based on average population data cannot yet predict personal risk with accuracy. Measurement limitations also remain a concern. Capturing impulses with microsecond rise times and extreme peak pressures requires specialized instrumentation [74]. Conventional sound level meters often saturate, leading to misleadingly low readings [75]. Without standardized high-fidelity measurement protocols, cross-study comparisons are inconsistent [76]. Regulatory diversity adds

another complication [77]. Military standards, industrial frameworks, and international guidelines emphasize different metrics, creating a lack of harmonization [77]. Laboratory-derived protector ratings often do not reflect reverberant or mixed environments encountered in practice [78]. Together, these factors limit the practical utility of existing models [79].

5.4. Future directions

Emerging approaches point toward promising solutions in hearing conservation strategies. Computational simulations that focus on the interactions within the ear canal enable modelling of acoustic behaviour without the necessity of human testing, although studies specifically addressing this simulation capability in the context of ear protection are limited [9]. Machine learning methods, when trained on large datasets, can integrate multiple descriptors to improve predictive accuracy and adaptability, particularly in device design and functionality [80]. Wearable dosimetry is advancing to provide real-time individualized exposure data, which can be linked to predictive algorithms to support adaptive conservation strategies in military and industrial environments [5].

The extension of assessment methods in the context of impulse noise to engineered noise controls offers potential improvements to hearing protection devices, though current literature addressing this transition requires more extensive validation [81]. Applying predictive frameworks to devices such as firearm suppressors illustrates their versatility and expands their purpose from personal to broader environmental protection [82]. Overall, the trend suggests a shift from single-metric models to hybrid frameworks that integrate both physiological and computational elements, although more research is needed to address individual variability and standardization [83]. While challenges remain, progress continues toward developing comprehensive and practical models proficient at guiding hearing conservation in diverse environments [84].

6. Conclusion

This review has highlighted the unique challenges of assessing impulse noise and predicting the effective sound pressure levels that reach the ear when hearing protectors are used. Unlike continuous noise, impulses combine extremely high peaks, rapid rise times, and very short durations, making them more hazardous and difficult to evaluate with conventional energy-based metrics. Research has progressed from simple energy descriptors toward more sophisticated models that integrate temporal, spectral, and physiological factors. Parametric and frequency-dependent models capture waveform details, while biophysical approaches simulate auditory responses. Recent hybrid frameworks combine computational modelling, statistical descriptors, and wearable dosimetry, offering more comprehensive and adaptable predictions.

When applied to hearing protectors, these models confirm that well-fitted devices can provide substantial attenuation but also reveal limitations such as nonlinear behaviour at extreme levels and variability in real-world conditions. Field data show that cumulative and waveform-sensitive metrics are better aligned with observed hearing outcomes than peak-only criteria, underlining the need for advanced approaches. Despite progress, challenges remain, including individual variability, measurement limitations, and

fragmented standards across military and industrial contexts. Future developments in computational simulation, machine learning, and real-time dosimetry are expected to bridge these gaps and support more accurate, personalized, and practical predictions. Accurate modelling of impulse noise is essential for hearing conservation. By aligning laboratory precision with field relevance and integrating new technologies, predictive frameworks can ensure effective protection for those exposed to hazardous acoustic environments.

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