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Safety Standards and Summaries for Laser, LED, and Sound Exposure in Public Displays and Wearables

Foundational Standards and Guidelines (Ranked by Relevance)

1. **IEC 60825-1:2014 – Safety of Laser Products (Equipment Classification & Requirements)** – *International Electrotechnical Commission.* This is the core global standard for classifying laser and high-intensity LED products by hazard level. It defines **laser Classes 1 (eye-safe) through 4 (high-danger)** based on accessible emission limits (AEL) derived from maximum permissible exposure (MPE) criteria [1] [2]. Classes 1M/2M address hazards when using magnifying optics, and LEDs are treated equivalently to lasers under this scheme [3] [4]. **Relevance:** Ensures that any lasers or intense LEDs in consumer or wearable devices (e.g. AR displays, projectors) are classified and labeled so that **Class 1 or 2** products can be used by the public without controls, whereas higher classes mandate safety measures [5] [6]. **Known limitations:** Focuses on acute injury thresholds (primarily eye/skin); assumes worst-case exposure (e.g. 0.25s aversion for Class 2 visible lasers) but does **not explicitly address cumulative long-term viewing** or any non-beam hazards. Regional enforcement can vary – e.g. it's a **voluntary standard, but often harmonized in regulations** (like EU's EN 60825-1) for product safety compliance.

2. **ANSI Z136.1 (2022) – American National Standard for Safe Use of Lasers** – *Laser Institute of America (LIA)/ANSI.* The flagship U.S. laser safety standard, providing comprehensive guidance on laser hazard classification, exposure limits, and control measures [7]. It closely aligns with IEC 60825-1 on classification (Classes 1, 1M, 2, 2M, 3R, 3B, 4) and defines the **Maximum Permissible Exposure (MPE)** for eyes and skin across wavelengths and exposure durations [8] [9]. **Relevance:** Forms the basis of laser safety programs in industry, research, medicine, and entertainment in the US [7]. It guides design and use of laser-based *"sci-magic"* devices to ensure public and operator exposure stays below MPE limits, and recommends engineering controls (enclosures, interlocks) and labels per class. **Known limitations:** ANSI Z136 standards are **voluntary consensus** guidelines (not laws) [10], though often referenced by OSHA and FDA. They predominantly address occupational settings; direct consumer use is governed by federal laser product regulations (e.g. FDA 21 CFR 1040), which in practice are based on similar class limits. The standard does not cover non-laser "LED" hazards (those are handled by photobiological lamp standards) and does not differentiate general-public versus worker exposure – it assumes anyone should remain below the same MPE.

3. **IEC 62471:2006 – Photobiological Safety of Lamps and Lamp Systems** – *International Electrotechnical Commission.* This standard provides exposure limits and a **risk group** classification (RG 0/exempt, 1, 2, 3) for broadband optical sources like LEDs, lamps, and displays. It addresses hazards such as **blue-light retinal injury, UV skin/eye damage, and IR thermal effects** from continuous or pulsed incoherent light [11] [12]. High-brightness LEDs and fiber-optic sources, which were historically classified as Class 1–3 lasers, are now evaluated under IEC 62471's scheme [13] [14].

Relevance: Ensures **LED-based wearables or public displays** (e.g. AR headsets' micro-LED projectors, LED billboards, "light spell" effects) do not exceed safe radiance or irradiance levels for eye and skin. For example, most consumer LEDs fall in **Exempt or RG1 (no risk)**, with only extremely bright or blue-rich sources approaching RG2 (moderate risk) or RG3 (high risk) [15] [16]. Implementing this standard helps device makers design optics and safety features (like diffusers or exposure limits) to avoid retinal hazards. **Known limitations:** Applies to **incoherent broadband sources**; lasers are excluded and covered by IEC 60825. The risk groups are defined for worst-case viewing conditions and do **not directly translate to time-based exposure limits** for users – additional guidance (IEC TR 62471-2) is needed for assessing actual use conditions. Also, general-public vs occupational distinctions are not explicit (like ICNIRP, it assumes limits that protect essentially all persons). Regulatory adoption varies (e.g. EU's Low Voltage Directive cites EN 62471 for LED product safety).

4. **OSHA 29 CFR 1910.95 – Occupational Noise Exposure (Permissible Exposure Limits)** – *U.S. Occupational Safety & Health Administration.* The federal regulation defining workplace noise exposure limits: an **8-hour time-weighted average (TWA) of 90 dBA** is the Permissible Exposure Limit (PEL), with a 5 dB exchange rate (meaning allowable exposure time halves with each +5 dB) [17] [18]. It also sets an absolute ceiling: **115 dBA for continuous noise** (no unprotected exposure longer than 15 minutes at 115 dBA), and **140 dB peak** for impulsive noise (gunshots, etc.) must not be exceeded [19]. Employers must implement hearing conservation programs if worker noise exceeds **85 dBA TWA (action level)**. **Relevance:** While aimed at occupational settings, these limits inform safe design of public-facing systems – e.g. a wearable device or interactive display should not continuously expose users or bystanders to >85–90 dBA without control, to prevent hearing damage. For instance, if a "sound magic" gadget is used in a show, keeping its output within OSHA limits ensures it's also likely safe for a general audience in the short term. **Known limitations:** OSHA's PEL (90 dBA/8h) is **less strict than modern consensus** – it permits about 25% of exposed people to develop hearing loss over a career [20] [21]. It's legally enforceable in U.S. workplaces but does **not apply to general public or consumer products**. Also, the 5 dB exchange rate is considered outdated (NIOSH and WHO recommend 3 dB). No specific coverage of ultrasonic or very low-frequency noise.

5. **NIOSH Criteria (1998) – Recommended Exposure Limit for Occupational Noise** – *National Institute for Occupational Safety and Health, U.S.* NIOSH recommends a more conservative noise exposure limit of **85 dBA TWA for 8 hours** (3 dB exchange rate) to better protect hearing [20] [21]. At the 85 dBA limit over 40 years, ~8% of workers may incur hearing loss, compared to 25% under the OSHA 90 dB PEL [22] [23]. It also recommends a 140 dB peak limit for impulsive noise (same as OSHA) and promotes using engineering controls and hearing protection well before reaching these levels. **Relevance:** NIOSH's REL is often considered a *gold standard* for hearing safety – it underpins many international and industry guidelines (e.g. WHO safe listening). For wearable tech and public installations, designing to 85 dBA or below for any prolonged user exposure (and using 3 dB exchange for shorter durations) ensures a high level of safety. For example, if a wearable AR device emits sound, keeping its output within NIOSH limits would allow even continuous use with minimal risk of NIHL (noise-induced hearing loss). **Known limitations:** This is **guidance, not law**, and focuses on occupational exposure – it assumes a standard work schedule (e.g. 8 hours/day, 5 days/week). It does not explicitly address vulnerable populations (children, those with existing hearing sensitivities) or combined exposure (e.g. noise + ototoxic chemicals). Nonetheless, it provides the scientific basis that many regulations later adopt or build upon.

6. **ICNIRP Guidelines (2013) – Laser Radiation Exposure Limits** – *International Commission on Non-Ionizing Radiation Protection.* Authoritative global guidelines specifying the **maximum safe exposure levels for laser radiation** (180 nm–1 mm wavelengths) to eyes and skin [24] [25]. They update earlier (1996/2000) limits with refined models for retinal thermal damage, pulse-duration effects, etc. The ICNIRP exposure limits (ELs) are used to derive the MPEs in many standards (like ANSI and IEC) [26] [27]. Notably, **no distinction is made between occupational and general public exposure** – because laser injuries are threshold-based and acute, the same limits apply to all individuals for safety [28]. **Relevance:** This is the scientific bedrock for laser safety in any context, including novel consumer tech. For example, if a wearable uses an eye-projection laser display, one ensures the emitted beam at the eye is below ICNIRP's exposure limit for that wavelength/duration, thus preventing retinal injury. ICNIRP's work often informs **regulations worldwide** (EU regulations directly adopted ICNIRP limits for workplace laser exposure). **Known limitations:** These guidelines address **acute bioeffects (within seconds to hours)** – they acknowledge a lack of knowledge on chronic, low-level effects over years [29]. Thus, they are very protective against immediate injury but do not guarantee that lifelong tiny exposures have zero risk. Medical laser exposures (e.g. therapeutic use) are outside scope, and the guidelines assume a healthy eye (special cases like photosensitive individuals or infants may need extra caution even if within limits).

7. **ICNIRP Guidelines (2013) – Incoherent Optical (Visible & IR) Radiation** – *ICNIRP.* A companion to the laser limits, this provides exposure limit values for broadband **LEDs, lamps, and other non-laser sources** from 380 nm to 1400 nm (visible-to-IR) for eye and skin safety [30] [31]. It includes the blue-light hazard function for retinal injury and IR limits to prevent corneal/lens damage. As with lasers, **no separate public vs worker limits** are set – except a special consideration for young children's eyes regarding blue-light (aphakic) hazard [32]. **Relevance:** It underpins safety assessments for bright AR/VR displays, LED-based "illusions," or any lighting that people view for extended periods. For instance, it defines the maximum luminance or radiance an AR headset's display can have so that an 8-hour use wouldn't harm the retina. Many national standards (e.g. European Directive 2006/25/EC for workplace lighting) directly reference these ICNIRP limits [33] [34]. **Known limitations:** Only acute (up to 8 hours) exposure effects are considered, based on threshold data – chronic low-level effects (over years) are uncertain [35]. The guidelines caution that they don't address **photosensitive patients or medical device use**, and they focus on injury (not subtle effects like circadian disruption or blue-light macular degeneration hypotheses). Additionally, UV hazards (<380 nm) are covered in separate guidance, so this standard must be used in conjunction with UV standards for full-spectrum sources.

8. **IEC 62368-1:2020 – Audio/Video & IT Equipment Safety (Hazard-Based)** – *International Electrotechnical Commission.* A broad product safety standard covering modern consumer electronics, including **AR/VR devices, wearables, and multimedia equipment**. Instead of prescriptive rules, it uses a hazard-based approach: identify energy sources (electrical, thermal, mechanical, **optical radiation, sound**, etc.) and apply safeguards to keep user exposure below hazard thresholds. For optical radiation, IEC 62368-1 requires that any integrated laser or LED emitter in a product **meets IEC 60825-1 or IEC 62471 class limits** for user-accessible radiation [36] [37]. For acoustics, it references standards like EN 50332 to limit headphone/earphone output – generally capping continuous sound to ~85 dBA with warnings up to 100 dBA for personal audio devices [38] [39]. **Relevance:** This is often the **compliance standard for consumer tech**. A wearable "sci-magic" gadget with lasers and speakers would be certified under IEC 62368-1, ensuring it doesn't present burn, shock, optical, or auditory hazards. It effectively bundles the laser/LED and noise limits from

specialized standards into one framework for designers. **Known limitations:** Being very broad, it **relies on other standards** for specifics (e.g. it will tell you to test lasers per 60825, sound per IEC 60065/EN50332). Manufacturers must interpret some general criteria for novel scenarios. Also, it primarily protects against injury – for example, the audio limits are aimed at preventing hearing loss but might not address annoyance or subtle health effects. Regional variants (EN 62368-1, UL 62368-1) may add requirements, and it's updated as new hazards emerge (e.g. guidance for ultrafast pulsed lasers or new headphone types may be added in technical reports).

9. **WHO Environmental Noise Guidelines (1999 & 2018)** – *World Health Organization.* These guidelines cover **general public exposure** to noise in community and leisure settings, synthesizing health research. WHO 1999 recommended that to avoid hearing impairment in the population, **24-hour LAeq should not exceed 70 dB(A)** over a lifetime [40]. For night noise, to prevent sleep disturbance, they advised ~30 dB(A) in bedrooms. Peak sound levels at events should stay below **140 dB** for adults and **120 dB for children** to prevent acute acoustic trauma [41]. The 2018 update (for Europe) further set chronic noise exposure guidelines (e.g. <53 dB L_den for road traffic to reduce cardiovascular and annoyance risks) and emphasized lower levels for sensitive groups. **Relevance:** Provides a benchmark for "safe" noise in public venues and devices beyond workplaces. For instance, if designing an interactive public display with sound effects, keeping typical exposure around or below 70 dB(A) means **virtually no risk of hearing damage to bystanders** [42]. Similarly, ensuring one-time demo sound blasts stay under 140 dB peak protects everyone's ears. These guidelines also inspire regulations – e.g. many countries impose 100 dB limits at concerts and require hearing protection options, aligning with WHO's calls for safe leisure noise. **Known limitations:** The guidelines are **non-binding** and mainly address broad health outcomes (hearing loss, annoyance, sleep disruption) in communities. Implementing them can be challenging (e.g. 70 dB LAeq_24h is easily exceeded in cities). They do not directly address the short-term loud music exposures common in personal device use – hence WHO has separate "safe listening" standards for devices and venues. Also, the 2018 guidelines note only **conditional recommendations** for some noise sources due to limited quality of evidence, reflecting uncertainty in exact risk thresholds for issues like hypertension from noise.

10. **CIE S 009 / CIE 245:2021 – Blue-Light and Infrared Eye Safety Reports** – *International Commission on Illumination (CIE).* These technical reports focus on specific modern concerns: **blue-light hazard from LEDs and displays**, and **long-duration IR exposure from eye-tracking or gaze-controlled devices**. They consolidate scientific evidence and confirm that current exposure limits (ICNIRP/IEC) are generally protective. For example, CIE 245:2021 examined IR eye-trackers used 10–12 hours daily (for assistive communication) and found typical devices **do not exceed exposure limits**, with the most restrictive constraint being avoiding chronic lens heating (to prevent cataracts) [43] [44]. **Relevance:** These are **authoritative analyses for new consumer use-cases** – e.g. AR/VR headsets with integrated eye-tracking, or high-brightness VR displays. They provide reassurance that adhering to standards like IEC 62471 (for blue-light) and ICNIRP limits truly protects users even during extended use [45] [46]. They also highlight any gaps: CIE notes that very long daily exposures are in line with existing limits but suggests continued research on cumulative effects. **Known limitations:** Such reports often focus on *specific scenarios* (e.g. a narrow set of IR wavelengths for eye trackers), so their conclusions may not generalize to all devices. They assume devices meet current standards – so they validate the standards rather than propose new limits. As "consensus reports," they don't carry regulatory force but serve to inform updates to standards and calm safety concerns. Also, CIE documents must usually be purchased (except summaries), so accessibility can be limited.

Key Summaries, Analyses, and Recent Developments

1. **Lasermet (2018) – *Overview of LED and Laser Classification*** [47] [1] – An expert summary explaining the **IEC 60825-1:2001 and later** classification system, including the introduction of Classes 1M, 2M, 3R and phase-out of old Class IIIa. It clarifies that IEC laser classes apply to LEDs as well (generally placing most LEDs in lower classes) [3]. The piece provides practical descriptions of each class (e.g. Class 1 is "eye-safe under all conditions," Class 2 is safe via blink reflex for <0.25 s exposure) and tabulates their requirements [48] [49]. *Relevance:* Great for understanding how to classify a novel device that uses lasers or high-output LEDs – important for **public-facing products** to know if they must be Class 1/2 (no user controls needed) or higher (needing training or interlocks). *Limitations:* As a secondary source, it interprets the standard (not an official standard itself). It notes no known Class 4 LEDs, which could change with technology. Always refer to the actual IEC standard for compliance, but this guide aids interpretation.

2. **OSHA Technical Manual – *Laser Hazards* (Section III, Ch.6)** [50] [51] – An OSHA guidance document (updated 2014) summarizing bioeffects of lasers and detailing hazard classifications. It connects ANSI Z136.1 and FDA regulations, explaining that manufacturers must label lasers per Class I–IV, and that class is based on the laser's Accessible Emission Limit, which in turn is derived from the MPE (maximum permissible exposure) [51]. It also describes control measures for each class and notes special designations like Class I.A for lasers not intended for viewing (e.g. supermarket scanners) [52] [53]. *Relevance:* Provides **authoritative, plain-language insight** into how laser output correlates to hazards (e.g. why <1 mW visible lasers are Class II and considered low risk [54]). Useful for anyone implementing lasers in products to understand required safeguards at each class. OSHA's perspective ensures that even in **occupational or public venue use**, lasers are handled safely according to their class. *Limitations:* Focuses on worker safety and U.S. regulatory context (mentions FDA/CDRH rules). It predates the latest IEC updates (it uses Class IIIA/IIIB nomenclature alongside 3R/3B) and doesn't address LED lamps. Still, fundamentals remain valid.

3. **Seibersdorf Labs White Paper (2017) – *IEC 60825-1 Edition 3 Changes*** [55] [56] – An in-depth analysis of the 2014 revision of IEC 60825-1. It highlights technical changes like removal of the "Class 3B under certain viewing conditions" loophole (old Condition 2 for telescopic optics) [57], introduction of a new Class 1C for certain laser products, and clarifications on measuring extended-source lasers vs. **laser-illuminated projectors**. Critically, it discusses harmonization issues with the EU's worker safety Optical Radiation Directive: Edition 3's slightly higher accessible emission limits for some classes vs. older limits and how that might conflict with fixed exposure limits in regulations [33] [58]. *Relevance:* For developers of **cutting-edge laser consumer products (like pico-projectors, LiDAR, or "light spells")**, this reveals the rationale behind classification rules and the importance of compliance with the latest standard. It's also useful for safety engineers to ensure measurement methods are up-to-date (since Edition 3 changed certain testing setups). *Limitations:* It is somewhat technical and assumes familiarity with prior IEC 60825-1 editions. Also, parts of it focus on European legal integration (which may not directly impact a product outside the EU). But it's authoritative, written by laser safety experts involved in standards-making.

4. **Leontopoulos et al. (2023) – *Blue Light Hazard in VR Head-Mounted Displays*** [45] [46] – A recent study published in *Lighting Research & Technology* assessing whether high-brightness VR headsets pose **blue-light retinal hazards**. It compared the blue-light weighted radiance of modern VR displays (including a prototype up to 6000 cd/m²) against the ICNIRP/IEC exposure limits. The

conclusion: even for an 8-hour usage at minimal viewing distance (~15 mm), current VR devices remain **below the hazard thresholds** for blue light [59] [60]. *Relevance:* Timely reassurance that immersive wearables with ultra-bright screens (for daylight visibility) are safe under photobiological standards. This is directly relevant to **AR/MR glasses or any "magic visor"** a user might wear for extended periods. It validates that compliance with IEC 62471 (blue-light limits) is typically achieved in well-designed displays. *Limitations:* Focuses only on blue-light photochemical risk to the retina; it doesn't address other concerns like flicker, thermal effects, or visual discomfort. It assumes proper use (e.g. not staring into external sun through the optics) and that the device's spectral output is similar to those tested. Nonetheless, it provides a scientific basis that standard-conforming displays should not cause retinal injury.

5. **WHO-ITU (2019) – *Global Standard for Safe Listening Devices*** [61] [62] – A World Health Organization initiative with the International Telecommunication Union, creating guidelines for personal audio devices (phones, music players) to prevent noise-induced hearing loss. It recommends built-in **dosimetry features** that track a user's sound exposure over time and volume limit options. Notably, it suggests default modes like **80 dB(A) for 40 hours/week** as a safe exposure allowance (roughly equivalent to NIOSH 85 dBA for 8h/day) [63] [61]. Devices should warn users when they exceed safe dose and have parental volume control for children [64] [62]. *Relevance:* This standard is directly applicable to **wearable tech with audio output** (smart headphones, AR glasses with built-in earbuds). Following it means the device will autonomously keep users' listening habits in check (e.g. lowering volume after long loud periods or giving health warnings). For public interactive systems, the concept of limiting weekly dose can be extrapolated to ensure frequent attendees or operators aren't over-exposed. *Limitations:* It's a **voluntary guideline** and primarily aimed at manufacturers and regulators; compliance relies on industry adoption or legislation. It addresses only hearing loss risk – not other effects of loud sound (e.g. annoyance or cardiac effects). Also, it assumes users will heed warnings or use the safety features – human behavior is a factor. In 2022, WHO released a similar standard for safe listening **venues/events**, which complements this by targeting concerts and clubs.

6. **WHO (2022) – *Global Standard for Safe Listening Venues and Events*** – A WHO guideline to make concerts, festivals, clubs and public events safer for hearing. It advises measures like: an average sound level **limit of 100 dB LAeq over 15 minutes** in venues, provision of free earplugs, "quiet zones" for recovery, and real-time sound monitoring by trained staff. It also encourages venues to display decibel levels and warnings. *Relevance:* For any high-volume public display or performance using sound (e.g. a "magical sound spectacle"), these practices help protect the audience's hearing without compromising the experience. It essentially extends occupational-type protections to leisure events (recognizing that repeated high exposures among the public, especially youth, contribute to hearing loss). *Limitations:* It's a global recommendation – actual enforcement depends on local adoption (some countries have enacted laws at or near these levels, others have none). The 100 dB limit is still higher than occupational limits (which roughly correspond to 85–90 dB over 8h); it balances enjoyment and safety, but some individuals could be vulnerable even below 100 dB. The guidance is broad, so implementing all aspects (like sound level averaging, providing quiet rooms) can be challenging for small event organizers.

7. **Vishay Semiconductor App Note (2021) – *Eye Safety for LEDs*** [11] [12] – A technical note outlining how eye safety standards apply to LEDs. It explains that earlier editions of IEC 60825-1 *included* LEDs, but now **LED products are assessed under IEC 62471** (the lamp safety standard) because that is

more appropriate for their incoherent light [11] [12]. It assures that LEDs which were Class 1 under laser standards will generally fall in the **Exempt group** under 62471, meaning inherently safe [65]. It also discusses specific LED types: IR LEDs (infrared emitters) are often "eye-safe" under both old and new standards (e.g. all Vishay IR diodes were Class 1/Exempt) [66] [67], and visible LEDs usually pose very low risk except possibly for high-blue-intensity sources (blue light hazard). *Relevance:* This is a **practical guide for product engineers** using LEDs for illumination, sensing or data transmission in consumer products. It helps ensure **compliance and safety labeling** are correct (e.g. not mislabeling an LED product as a laser class). It's particularly relevant if your device uses high-brightness LEDs near the eyes (IR eye tracker illuminators, status indicators, etc.), confirming that following photobiological safety testing is necessary but typically these LEDs are safe by design. *Limitations:* As a manufacturer's note, it's focused on their product range and assumes normal usage conditions. It doesn't cover unusual scenarios (e.g. LEDs viewed through magnifiers or multiple LEDs in array which could sum to higher intensity). Nonetheless, it's a concise secondary source reflecting current standard practice for LED eye safety.

8. **Gross et al. (2025) – *Optical Safety Requirements for Eye-Tracking Sensors*** – A forthcoming overview (Journal of Laser Applications) addressing the patchwork of standards for infrared eye trackers in VR/AR and other devices. It points out that while IEC 60825-1 and IEC 62471 provide exposure limits, there was ambiguity for **very long daily exposure** from IR LEDs used in eye trackers. It reviews current limits (including ICNIRP and CIE findings) and notes potential gaps, such as the lack of a distinct category for chronic low-level exposure to the eye. The authors ultimately suggest that existing limits (notably the lens IR exposure limit) are adequate for even 12+ hours/day use, but careful hazard analysis is needed case-by-case. *Relevance:* Eye tracking is integral to many new wearable interfaces (gaze control, foveated displays). This analysis ensures that such systems remain within safe IR levels even if someone uses an AR headset all day. It helps standards bodies decide if adjustments are needed for chronic exposure assumptions. For developers, it reinforces the need to adhere to **current standards (no "free pass" for seemingly low-power LEDs)** and possibly to implement extra safety factors for continuous use. *Limitations:* We only have a high-level summary (as the full paper is anticipated); it mostly aggregates existing standards rather than introducing new exposure criteria. It's forward-looking, so regulators have not yet incorporated any new recommendations that might come from it. But it serves as a check that our **wearable devices comply not just in theory (per standard), but in realistic use** over long durations.

9. **FDA Laser Performance Standard (21 CFR 1040.10) – *U.S. Laser Product Requirements*** – The U.S. regulation for laser products (currently largely harmonized with IEC classes). It mandates safety features like emission indicators, key switches, interlocks for high classes, and specific warning labels for each class. For example, a Class II or IIIa laser product in the U.S. must have a "Caution" or "Danger" label with the laser's class and output, and Class IIIb/IV products require a key switch and remote interlock connector. *Relevance:* Any **consumer-facing laser device in the U.S.** (laser pointers, projectors, AR glasses with lasers) must meet these requirements in addition to exposure limits. It ensures a baseline of safety engineering – e.g. a high-power wearable laser can't accidentally activate without a key, and users are warned of beam hazards. *Known limitations:* The FDA rules, while authoritative, have not fully caught up with IEC's newer class nomenclature (they still use I–IV, IIIa etc., though FDA recognizes IEC classes in practice via guidance). Also, they do not cover LED-only products. This is a **region-specific compliance standard**, but it's founded on the same hazard principles discussed above. Notably, FDA can grant variances for laser light shows above Class IIIb if

strict safety procedures are followed – highlighting that regulations sometimes allow exceptions under controlled conditions, which is outside normal consumer use.

10. **ISO 1999:2013 (Acoustics) – *Estimating Noise-Induced Hearing Loss*** – An international standard (also adopted as ANSI S3.44) that provides a model to predict the percentage of people who will suffer hearing impairment given a certain noise exposure level over time [68] [42]. It essentially underpins guidelines like WHO's: for instance, ISO 1999 data indicate that an LAeq,8h of 75 dB over a lifetime is expected to cause negligible hearing loss in an exposed population [69] [70], which led to the WHO's 70 dB LAeq,24h general safety recommendation. *Relevance:* This gives a quantitative basis for setting "safe" noise limits for the public and workers. A device designer can use it to estimate risk – e.g. if a wearable speaker exposes users to 85 dBA for 2 hours daily, ISO 1999 can predict the probable hearing loss distribution after years of use. It's crucial for **evidence-based standards** like those above (NIOSH, WHO). *Limitations:* The standard deals with statistical populations and typical susceptibilities, not individual variability – some people have damage at lower exposures, some tolerate more. It doesn't address non-hearing effects of noise. It also assumes mostly steady noise and primarily occupational exposures, so applying it to intermittent or leisure noise requires expert interpretation. Nonetheless, it's a fundamental reference for any detailed acoustic safety analysis.

Ranking Rationale: The foundational documents are ordered by direct applicability to **public-facing wearable tech** and the authority of the issuing body. For example, IEC 60825-1 and ANSI Z136.1 are top-ranked as they define the **core laser safety classes and limits** that any product with lasers/LEDs must adhere to. Occupational and general noise standards follow, as hearing safety is equally critical for devices emitting sound. ICNIRP and WHO guidelines bridge between pure safety limits and public health perspectives, reinforcing protections for all users. IEC 62368-1 is included for its holistic approach to product safety, ensuring multi-hazard compliance in design. In the secondary sources, practical summaries (Lasermet, OSHA) and recent studies are highlighted by how they clarify or stress-test these safety limits in real-world scenarios (like VR use, long-duration exposures, etc.), with those directly relevant to wearables (eye-tracking, AR/VR displays, personal audio) given higher priority. Each entry notes scope and limitations so one can understand the context and any gaps, which is crucial in applying these standards to innovative "sci-magic" devices responsibly.

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