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RESEARCH PROGRAMME
SPECTRA

WORLDWIDE EVIDENCE REVIEW

Bluetooth Headphones and RF-EMF in Teenage Tinnitus

Chronic in-ear wireless exposure as a complementary environmental toxin candidate: an Environmental Physiology evidence review

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ABSTRACT

Tinnitus in teenagers and young adults now arrives through a device that delivers two exposures at once. Since the AirPods launch in December 2016, true wireless stereo (TWS) earbuds have made continuous, bilateral, cochlea-adjacent radiofrequency electromagnetic field (RF-EMF) emission a default condition of daily life for hundreds of millions of young people, layered onto the acoustic dose the same earbuds deliver. Over the same decade, clinicians in EFEIA's network and the professionals it trains have seen the number of teenagers and young adults presenting with tinnitus rise visibly. This review exists to study that increase, and it asks whether the second exposure deserves to be treated as a complementary environmental toxin candidate alongside the established acoustic axis. It does not ask whether Bluetooth causes tinnitus. No human study has tested that, and the review says so plainly.

The argument has two halves. First, adolescents who develop tinnitus carry a physiological vulnerability profile that is now well characterized: cochlear synaptopathy that precedes audiometric loss, reduced sound-level tolerance at normal thresholds, elevated central gain, and disturbed sleep and stress physiology. Second, non-thermal RF-EMF perturbs several of these same systems in animal models and, more weakly, in human provocation studies. Where the halves overlap, RF-EMF is a plausible and modifiable load on an already stressed auditory periphery. Where they do not, the review says that too.

The review documents an empty intersection. The mainstream direct epidemiology on RF-EMF and tinnitus is null, but every study in it measured legacy phone-to-ear call time, a profile dosimetrically distinct from chronic earbud wear. The only two human studies of Bluetooth headsets and hearing are acute and small. No cohort has recorded earbud wear time and tinnitus incidence together. That absence bounds what can be claimed in either direction and defines the research agenda.

Every source in the review was resolved at the primary level: the link was opened, the claim attributed to it was located in the text, and authors, year, journal, volume, pages and DOI were confirmed. Sources that could not be confirmed were left out; figures that could not be

located in their source are not repeated. The 24 core sources are profiled in a companion document, and every reference is standardized to APA 7th edition with DOI. Regulatory status is current to September 2026.

1. Background and scope

Tinnitus, the perception of sound without an external source, affects roughly 14 percent of adults worldwide, about 740 million people, and severe tinnitus affects about 2 percent (Jarach et al., 2022). Among children and teenagers the picture is more variable and less well tracked: prevalence estimates run from 3.1 percent in a 43,064-child school screening in Warsaw (Raj-Koziak et al., 2021) to 54.7 percent by questionnaire in São Paulo adolescents (Sanchez et al., 2016), with 46 percent among first-year Korean secondary students (Rhee et al., 2020) and 47 percent among Palestinian teens aged 15 to 18 (Al-Lahhaam et al., 2026). The spread reflects case definition and ascertainment more than true variation, and it is a first reason to treat any single national figure with caution. What the surveys do not yet capture is what clinicians in EFEIA's network and the professionals it trains have observed directly over the past decade: more adolescents and young adults presenting with tinnitus, most of them with normal audiograms, most of them heavy users of in-ear wireless devices. That observation is the reason for this review.

Personal listening devices are the established environmental risk factor for this population. WHO estimates that over 1 billion young people are at risk of avoidable hearing loss from unsafe listening (World Health Organization, 2024a), and a systematic review of 33 studies places 24 percent of 12- to 34-year-olds in the unsafe range for personal listening devices alone (Dillard et al., 2022). That risk is regulated by an international standard, ITU-T H.870, which sets a weekly sound allowance for safe listening devices (ITU-T, 2022). What the standard does not address is the RF-EMF the same devices emit.

Whether RF-EMF affects hearing has been studied for two decades, and the mainstream reading is null at exposures below international guideline limits (Röösli et al., 2024; Auvinen et al., 2019). What is new is not the question but the exposure. A mobile phone held to the ear delivers intermittent, high specific absorption rate (SAR) exposure to one side of the head during calls. A pair of TWS earbuds delivers continuous, low-SAR, bilateral exposure adjacent to the cochlea and auditory nerve for as many hours a day as the wearer keeps them in. Every published cohort measured the first. None has measured the second.

EFEIA approaches this from the discipline it works in: electromagnetic hygiene, understood as the management of a person's electromagnetic environment in the same way that acoustic, thermal, chemical and light environments are managed. Within that discipline the question is not etiological. It is whether a given exposure raises or lowers physiological load on a vulnerable system, and whether reducing it changes anything measurable. This review is organized around that question, and it keeps three evidential tiers explicit throughout: established (consistent, replicated, primary-source findings), plausible (biologically coherent, supported by indirect or analogical evidence), and untested (no direct human study exists).

1.1 Scope

The review covers: (a) the epidemiology of adolescent and young-adult tinnitus, including the time-trend question; (b) the physiological vulnerability profile of young people with tinnitus, from cochlear synaptopathy to central gain and sleep; (c) the growth and characterization of the TWS exposure profile from 2016 to 2026, including Bluetooth protocol, power and dosimetry; (d) the acoustic-dose axis and its regulatory framework; (e) proposed non-thermal mechanisms by which RF-EMF could interact with the auditory system; (f) in vitro and animal evidence on RF-EMF and hearing; (g) human evidence on RF-EMF and hearing or tinnitus, including the Bluetooth-specific studies; (h) convergence between the two exposures, system by system; (i) sleep and stress as candidate mediating pathways; (j) regulatory, institutional and public positions; and (k) evidence gaps and a research agenda. Sources span the United States, Poland, Korea, Palestine, Brazil, Canada, Sweden, Finland, Austria, Italy, Greece, Turkey, Malaysia, France, Germany, Australia, China and the international bodies WHO, ICNIRP, IARC, ITU and Bluetooth SIG. Tinnitus management (sound therapy, cognitive behavioral therapy, amplification, cochlear implantation) is excluded by design.

2. Methods

2.1 Search strategy

Sources were retrieved through structured searches covering January 2005 to September 2026 in PubMed and MEDLINE, publisher platforms (Elsevier, Wiley, Oxford Academic, BMJ, Frontiers, Springer Nature, De Gruyter, Cambridge, SAGE, PLOS, JAMA Network, Taylor and Francis, Karger, Mary Ann Liebert, Spandidos), the EMF-Portal database, regulator and standards sites (WHO, ICNIRP, ARPANSA, IARC, NTP/NIEHS, ANSES, ITU, FCC, Bluetooth SIG), consensus and appeal sites (ICBE-EMF, EMFscientist.org, 5gappeal.eu, EUROPAEM, BioInitiative), advocacy and physician-network sites, fact-checking archives, and primary market-intelligence pages. Search terms combined tinnitus, teenagers, children, young adults, prevalence, cochlear synaptopathy, hidden hearing loss, hyperacusis, sound-level tolerance, central gain, headphones, earbuds, personal listening devices, Bluetooth, TWS, hearables, SAR, radiofrequency, RF-EMF, mobile phone, cochlea, outer hair cells, otoacoustic emissions, auditory brainstem response, schwannoma, acoustic neuroma, oxidative stress and sleep.

2.2 Inclusion and exclusion

Inclusion favored peer-reviewed primary studies, systematic reviews and meta-analyses, formal regulator documents, international standards, court rulings, and consensus statements from named commissions or academies. Advocacy syntheses were included only where they represent a documented institutional position and

are labeled as such. News and social media were excluded except as a route to a primary source or, in section 12, as the object of analysis.

2.3 Source verification and reference standardization

Every source cited in this review was checked for link resolution, presence of the specific claims and figures attributed to it, and accuracy of authors, year, journal, volume, issue, pages and DOI. Where a candidate source pointed to a secondary summary rather than the primary record, the primary record was used; where a claim could not be located in its source, the claim is not made; where a source could not be confirmed at the primary level, it was left out. A profile of each of the 24 core sources, with its quality score and stance, is recorded in the companion document *Bluetooth, RF-EMF and Tinnitus: Source Profiles* (EFEIA Institute, September 2026). References follow APA 7th edition with DOI links where available.

2.4 Quality scoring

Each of the 24 core sources carries a 0 to 10 quality score reported in Table 1: 9 to 10 for a peer-reviewed systematic review or meta-analysis, definitive prospective cohort, or formal WHO/IARC classification; 7 to 8 for a peer-reviewed original cohort, case-control or experimental study, a consensus statement from a named international commission, a major national-regulator opinion, an international standard, or a federal appellate ruling; 5 to 6 for a peer-reviewed narrative review, a market report with documented methodology, or an organized NGO or physician-network synthesis; 3 to 4 for an advocacy synthesis without formal peer review or a secondary aggregator; 0 to 2 for news or opinion (not used).

Table 1. At-a-glance table of the 24 core sources.

#	Title / Source	Type	Year	Country	Stance	Score
1	True wireless stereo earbuds market report, 2022–2030. Grand View Research	Market report	2022	Global	Informational	6.0
2	Earbuds market size report, 2035. Market Growth Reports	Market aggregator	2026	Global	Informational	4.0
3	AirPods unit-shipment estimates. Strategy Analytics / Counterpoint	Analyst estimate	2018 to 2022	Global	Informational	5.0
4	Common Sense census: media use by tweens and teens. Rideout et al.	NGO survey	2022	United States	Informational	8.0
5	RF-EMF and tinnitus, migraine, non-specific symptoms: systematic review. Röösli et al.	Systematic review	2024	Switzerland / intl	Skeptical	9.0
6	COSMOS headache, tinnitus and hearing loss. Auvinen et al.	Prospective cohort	2019	Sweden, Finland	Skeptical	9.0

#	Title / Source	Type	Year	Country	Stance	Score
7	WHO review finds no link. ARPANSA commentary	Regulator commentary	2024	Australia	Skeptical	7.5
8	Tinnitus and mobile phone use. Hutter et al.	Case-control	2010	Austria	Cautious support	6.5
9	Tinnitus and cell phones. Medeiros & Sanchez	Narrative review	2016	Brazil	Precautionary	6.0
10	International EMF Scientist Appeal	Consensus appeal	2015 to 2025	International	Concerned	7.0
11	The 5G Appeal	Consensus appeal	2017 to 2024	International	Concerned	7.0
12	ICBE-EMF: FCC and ICNIRP limit assumptions	Consensus review	2022	International	Precautionary	8.0
13	EUROPAEM EMF Guideline 2016. Belyaev et al.	Clinical guideline	2016	European Union	Precautionary	7.5
14	Risks from RF radiation from cell phones. Miller et al.	Narrative review	2019	Canada / US / intl	Precautionary	7.5
15	BioInitiative Report 2012: conclusions	Advocacy synthesis	2012	International	Concerned	5.0
16	ROS and cochlear damage after radiation. Gao et al.	Animal (ionizing)	2024	China	Analogy only	7.5
17	Ramazzini 1.8 GHz base-station bioassay. Falcioni et al.	Animal bioassay	2018	Italy	Precautionary	7.5
18	NTP TR-595 cell phone RFR in rats	Government bioassay	2018	United States	Cautious	9.0
19	IARC Monograph 102, RF-EMF Group 2B	Classification	2013	International	Cautious	9.5
20	Radiation: electromagnetic fields. WHO Q&A	Regulator position	2026	International	Skeptical / neutral	8.5
21	Mobile phones and health. ANSES	Regulator opinion	2019	France	Precautionary	8.0
22	Environmental Health Trust v. FCC	Court ruling	2021	United States	Regulatory gap	8.5
23	Bluetooth hazards. Physicians for Safe Technology	Physician network	2024	United States	Concerned	5.5
24	Recommendation ITU-T H.870 (V2). ITU-T with WHO	International standard	2022	International	Silent on RF-EMF	8.5

2.5 Conflict of interest

The author is founder and Chief Technology Officer of NOXTAK, maker of SPIRO electromagnetic-hygiene products, and is affiliated with the EFEIA Foundation and GEMS Academy. This commercial interest is directly relevant to the subject matter and is disclosed in full. No external grant funding was received for this review.

3. Tinnitus in teenagers and young adults as a physiologically vulnerable state

The first half of the argument rests on a body of work that has nothing to do with electromagnetic fields. Over the past two decades, clinical and mechanistic studies have characterized what is different about the auditory system of young people who develop tinnitus, and much of it lies below the audiogram. This section assembles that profile because the second half of the argument depends on it: an exposure matters to the extent that it acts on systems already under load.

3.1 Prevalence and case definition by country

Table 2. Tinnitus prevalence in children, adolescents and young adults, by country and study.

Country	Study	Population	Prevalence	Method
United States	Mahboubi et al. (2013)	3,520 NHANES participants, 12 to 19 y	7.5% any tinnitus; 4.7% recurrent	Interview
United States	Bhatt et al. (2016)	NHANES adults 18+	9.6% any; about 21 million adults	Interview
Poland	Raj-Koziak et al. (2021)	43,064 Warsaw schoolchildren, 7 to 12 y	3.1%	Screening questionnaire
Korea	Rhee et al. (2020)	1,593 first-year secondary students, nationwide	46.0% lifetime; 9.1% severe	Questionnaire with audiometry
Korea	Kim (2018)	1,587 KNHANES adolescents, 12 to 18 y	18.0%	Health examination
Palestine	Al-Lahhaam et al. (2026)	Adolescents 15 to 18 y	47%	Questionnaire
Palestine	Alqub et al. (2024)	University students	31%	Questionnaire
Brazil	Sanchez et al. (2016)	170 São Paulo adolescents, 11 to 17 y	54.7% questionnaire; 28.8% booth-verified	Both
Brazil	Coelho et al. (2007)	506 children, 5 to 12 y	37.7%	Interview
Belgium	Gilles et al. (2013)	3,892 secondary-school students	18.3% permanent; 74.9% temporary after noise	Questionnaire

Country	Study	Population	Prevalence	Method
India	Thirunavukkarasu & Geetha (2015)	Children under 18 presenting with ear or hearing complaints, Mysore	5.24% (clinic-based)	Case-file review
Canada	Ramage-Morin et al. (2019)	6,571 adults 19 to 79 y	37% past year; 46% in 19 to 29 y	Interview
Global	Jarach et al. (2022)	Adult meta-analysis	14.4% any; 2.3% severe	Meta-analysis

Three observations follow. First, the range is dominated by method: booth-verified perception in the São Paulo study was about half the questionnaire figure (28.8 versus 54.7 percent), the two Korean figures differ by a factor of two and a half because one measured lifetime tinnitus by questionnaire and the other current tinnitus by examination (Rhee et al., 2020; Kim, 2018), and the Warsaw figure comes from a screening question in a hearing-screening program (Raj-Koziak et al., 2021). Second, the young-adult band carries a high burden wherever it is measured separately: 46 percent of Canadians aged 19 to 29 reported past-year tinnitus, the highest of any age group and an inversion of the usual age gradient (Ramage-Morin et al., 2019). Third, the one Indian figure located is clinic-based, a one-year prevalence of 5.24 percent among children presenting with otological complaints at a tertiary center (Thirunavukkarasu & Geetha, 2015), and cannot be compared with population samples. Fourth, no study in the table measured RF-EMF exposure; the Korean, Belgian and Palestinian studies recorded earphone or leisure-noise exposure as a correlate, but as a proxy for acoustic dose.

3.2 The observed increase and the time-trend question

The increase in teenagers and young-adult tinnitus that EFEIA's clinicians and network professionals have observed over the past decade is the starting point of this review, and the review is honest about how far the published data have caught up with it. Repeated cross-sectional surveys with a consistent case definition are the only way to quantify a trend at population level, and they are scarce. NHANES asked about tinnitus in different waves with differing question wording and age ranges, and the youth analyses draw on single waves (Mahboubi et al., 2013; Bhatt et al., 2016). The KNHANES adolescent analysis used 2009 to 2011 examination data (Kim, 2018), and the later Korean school survey used a different instrument (Rhee et al., 2020), so the 18.0 to 46.0 percent difference between them is a difference of method, not a trend. The Swedish series of 1,285 high-school students aged 13 to 19 and the Belgian series of 3,892 secondary students document self-reported tinnitus and noise sensitivity as common in the 2000s and early 2010s, before TWS earbuds existed (Olsen Widén & Erlandsson, 2004; Gilles et al., 2013), which means the post-2016 exposure profile is layered on a burden that was already substantial, not creating one from nothing.

What the published data support is this: teenage tinnitus is common, it is under-recognized clinically, the youngest adult cohort now reports the highest prevalence in at least one national survey, and the most recent adolescent surveys return the highest figures on record for their countries. What the published data do not yet contain is a

repeated national series that quantifies the increase over calendar time. The inverted age gradient in Canada, in which the group that grew up with smartphones reports more tinnitus than every older group, is exactly the signature a cohort effect would leave, and it is consistent with what EFEIA sees in practice, but it is a single cross-section. This review therefore treats the increase as observed in clinical and professional practice and as consistent with the survey evidence, while stating that its size has not yet been measured in a repeated population series. Measuring it is the first item of the research agenda, and it is one of the reasons the exposure question is worth pursuing now rather than after the trend data arrive.

3.3 Cochlear synaptopathy and hidden hearing loss

The most important development in auditory science for this question is the discovery that the cochlea can lose a large fraction of its inner-hair-cell synapses to noise while thresholds recover to normal. Kujawa and Liberman (2009) showed in mice that a noise exposure producing only temporary threshold shift caused permanent loss of up to half the ribbon synapses on inner hair cells, followed by slow degeneration of the spiral ganglion neurons those synapses fed. The synapses that go first are those of the low-spontaneous-rate, high-threshold auditory nerve fibers that encode sound in noise (Furman et al., 2013). The condition has since been termed "hidden hearing loss" because the audiogram does not see it (Schaette & McAlpine, 2011).

The relevance to adolescents is direct. Liberman et al. (2016) compared college-age adults at high and low risk of noise exposure and found that the high-risk group, with normal audiograms, showed reduced summating-potential to action-potential ratios on electrocochleography, worse speech-in-noise performance, and more tinnitus and hyperacusis complaints, a pattern consistent with synaptopathy. Guest et al. (2017) found that young adults with tinnitus and normal audiograms showed no group difference in ABR wave I amplitude but did show elevated thresholds above 8 kHz, which complicates a simple synaptopathy account and points to the extended-high-frequency region as an early indicator. Bramhall et al. (2019) reviewed the human evidence and concluded that synaptopathy is likely present in humans but that its non-invasive detection remains unsettled. What is settled is that the teenage auditory periphery can carry substantial, invisible damage from acoustic dose alone.

3.4 Reduced sound-level tolerance and hyperacusis

Sanchez et al. (2016) supplied the clinical signature. Among 170 São Paulo adolescents aged 11 to 17, all with normal audiograms and normal distortion-product otoacoustic emissions, the variable that discriminated those who perceived tinnitus in the booth from those who did not was reduced sound-level tolerance, measured as lower loudness discomfort levels. Tinnitus in this group was not a consequence of audiometric loss; it was associated with a change in how loudness is processed. Hyperacusis and tinnitus co-occur far above chance in adults (Baguley, 2003; Cederroth et al., 2020), and the São Paulo data extend that overlap into adolescence.

3.5 Central gain, limbic and attentional networks

The central-gain model explains how reduced peripheral input can produce phantom perception. When cochlear output falls, whether from hair-cell loss, synaptopathy or both, central auditory neurons increase their gain to compensate, amplifying spontaneous activity into a perceived sound (Auerbach et al., 2014). Auerbach et al. (2014) framed tinnitus and hyperacusis as two outputs of the same gain control, tinnitus when the gain amplifies internal noise and hyperacusis when it amplifies external sound. Sedley (2019) reviewed the evidence and concluded that peripheral insults reliably raise central gain, but that gain alone has not been shown sufficient to explain tinnitus at the level of the individual, so that attention, prediction and memory processes must be part of any complete account. Rauschecker et al. (2010) proposed that a limbic noise-cancellation system normally suppresses phantom signals and that tinnitus becomes chronic when that system fails, linking the auditory pathway to the nucleus accumbens and ventromedial prefrontal cortex. De Ridder et al. (2011) documented hyperactivity in auditory, limbic and salience networks in chronic tinnitus. These models matter here because they identify the systems on which any additional stressor, acoustic or otherwise, would act: the cochlear synapse, the brainstem gain circuitry, and the limbic and attentional networks that determine whether a phantom signal becomes distressing.

3.6 Sleep, stress, HPA and autonomic correlates

Tinnitus in young people travels with disturbed sleep and stress physiology. Rhee et al. (2020) found sleep disturbance, depressed mood and stress among the strongest correlates of teenage tinnitus in Korea, and Kim (2018) found that tinnitus severity in KNHANES adolescents tracked stress, depression and suicidal ideation, with an adjusted odds ratio of 2.00 for depression. Hébert and Lupien (2007) showed blunted cortisol reactivity to stress in tinnitus sufferers, consistent with HPA-axis dysregulation, and Mazurek et al. (2012) reviewed the bidirectional relationship in which stress precipitates tinnitus and tinnitus sustains stress. Sleep loss lowers the threshold for phantom perception and raises distress (Crönlein et al., 2016). These correlates are relevant to the second half of the argument because sleep is one of the few outcomes for which RF-EMF has a reproducible human physiological signal (section 10).

3.7 Oxidative stress and mitochondrial biology of the cochlea

The cochlea is metabolically demanding and oxidatively vulnerable. Noise exposure generates reactive oxygen species (ROS) in the organ of Corti and stria vascularis within hours and continues for days, and the delayed component of hair-cell loss is ROS-mediated (Henderson et al., 2006). Fetoni et al. (2019) reviewed the redox pathways: mitochondrial superoxide, lipid peroxidation, glutathione depletion, and activation of apoptotic cascades. Kurabi et al. (2017) summarized the cellular mechanisms of noise-induced loss, in which oxidative stress converges with excitotoxicity at the inner-hair-cell synapse. Gao et al. (2024) showed that in a mouse model of ionizing radiation, stria vascularis damage preceded outer-hair-cell loss and was prevented by N-acetylcysteine.

That study is cited here only as a demonstration that the strial redox pathway exists and is druggable; it is not RF-EMF evidence.

3.8 Genetic and developmental susceptibility

Tinnitus has a heritable component. Twin and adoption studies estimate the heritability of clinically significant tinnitus at roughly 40 percent, higher for bilateral tinnitus and in men (Maas et al., 2017; Cederroth et al., 2019). Developmental timing matters because the teenage auditory system is still maturing centrally, and because exposure during this window sets the baseline from which later age-related loss proceeds. The relevant point for an exposome framing is that susceptibility varies, and that a subgroup of adolescents will carry higher vulnerability to any auditory stressor.

4. The exposure: chronic in-ear Bluetooth as a novel exposure profile

4.1 The 2016 to 2026 growth of TWS earbuds

The TWS category did not exist at meaningful scale before December 2016. Apple does not disclose unit sales, so the widely cited AirPods trajectory rests on analyst estimates: approximately 15 million units in 2017, 35 million in 2018, 60 million in 2019, and above 100 million per year from 2020, according to Strategy Analytics and Counterpoint Research estimates published between 2018 and 2022. These figures are directionally consistent across analysts but must be cited as estimates. Launch dates are verifiable against Apple's product record: AirPods (December 2016), AirPods 2 (March 2019), AirPods Pro (October 2019), AirPods Max (December 2020), AirPods 3 (October 2021), AirPods Pro 2 (September 2022), AirPods 4 (September 2024).

On market scale, Grand View Research (2022) valued the global TWS earbud market at USD 35.37 billion in 2021 and projected USD 563.2 billion by 2030 at a 34.9 percent compound annual growth rate, with Apple leading ahead of Samsung, Sony, Jabra, Bose, Sennheiser, Xiaomi and Huawei. The report gives revenue, not units, so unit forecasts circulating in secondary sources should not be cited to it. The defensible statement is that the annual exposure denominator grew by roughly an order of magnitude between 2016 and 2024 and continues to grow at a double-digit rate.

4.2 Daily wear time and media-use data

In a probability-based United States sample (n = 1,306), children aged 8 to 12 averaged 5 hours 33 minutes and teenagers aged 13 to 18 averaged 8 hours 39 minutes of daily entertainment screen media, with music listening a substantial component (Rideout et al., 2022). The survey does not distinguish wired from Bluetooth listening, but it establishes the duration term: daily personal-audio exposure in this population is measured in hours, and the

survey wave that recorded it postdates the TWS transition. Korean adolescents reporting heavy earphone use had substantially higher tinnitus odds (Rhee et al., 2020). Nighttime earbud use for sleep, a growing behavior, extends the exposure into the one period when acoustic dose would otherwise be zero (section 10).

4.3 Bluetooth Classic versus LE Audio, power classes, duty cycle and modulation

Two technical points need to be stated before the dosimetry, because both are often misstated in public discussion. TWS earbuds have historically streamed audio over Bluetooth Classic (BR/EDR) using the A2DP profile, not over Bluetooth Low Energy in a continuous transmit mode. LE Audio, which runs over Bluetooth Low Energy using the LC3 codec, is the newer architecture; the Bluetooth Core Specification 5.3 was published on 13 July 2021 (Bluetooth SIG, 2021) and the LE Audio specification set was completed on 12 July 2022 (Bluetooth SIG, 2022).

The core specification defines transmit power classes: Class 1 up to 100 mW (20 dBm), Class 2 up to 2.5 mW (4 dBm), and Class 3 up to 1 mW (0 dBm); the LE physical layer permits 0.01 mW to 100 mW (Bluetooth SIG, 2021). Most earbuds are Class 2. Bluetooth operates in the 2.400 to 2.4835 GHz ISM band with frequency hopping across 79 channels (Classic) or 40 channels (LE), using Gaussian frequency-shift keying or, for EDR, phase-shift keying, and a duty cycle during A2DP streaming that varies with codec bit rate and link quality but is well below a continuous carrier. In TWS pairs, one earbud typically holds the phone link and relays to the other, or both receive a broadcast stream in newer LE Audio designs, so laterality of exposure differs by product generation.

4.4 Dosimetry: SAR and field strength at the ear, cochlea and auditory nerve

The regulatory reference for head exposure is local SAR: 1.6 W/kg averaged over 1 g of tissue in the United States (Federal Communications Commission, 1996) and 2.0 W/kg averaged over 10 g under ICNIRP guidelines (ICNIRP, 2020). Manufacturer equipment-authorization filings with the FCC report head SAR for AirPods models on the order of 0.07 to 0.10 W/kg, roughly 15 to 25 times below the FCC limit. These values come from manufacturer filings reported through secondary channels rather than independent peer-reviewed dosimetry, and first-generation AirPods figures are inconsistent across sources; they are flagged accordingly (Physicians for Safe Technology, 2024).

Independent dosimetry of Bluetooth earbuds remains thin, and this review reports what exists at its true level of rigor. The one peer-reviewed measurement of wireless headsets in a standardized setting comes from the IT'IS Foundation, which determined SAR from Bluetooth hands-free kits experimentally alongside wired kits and found that both reduce head exposure by well over an order of magnitude compared with a phone at the ear (Kühn et al., 2009); it measured single-ear call headsets of that era, not TWS earbuds streaming music, so it bounds the peak-exposure question without characterizing chronic bilateral wear. Manufacturer equipment-authorization filings with the FCC for current Apple products give head SAR of 0.39 W/kg and a

worst-case body-worn value of 1.18 W/kg for AirPods Pro 2 (FCC IDs BCG-A3047 and BCG-A3048), as reported from the filing by Science Feedback (2023), and roughly 0.11 W/kg in the in-ear orientation and 1.19 W/kg in the antenna-facing body orientation for AirPods 4 (FCC ID BCG-A3053; Apple Inc., 2024), all below the 1.6 W/kg limit averaged over one gram. The high body-worn figures reflect the antenna-facing-phantom worst case required by the test protocol, not the in-ear geometry. These values were read through secondary reports of the filings rather than from the raw test reports and are labeled accordingly. Two independent broadband-field studies of commercial earbuds, including AirPods, estimate SAR at roughly 0.006 to 0.017 W/kg across idle, music and calling modes, about one percent of the limit (Obinor & Akpolile, 2026, which reports and extends an earlier 2024 broadband survey); both derive SAR from measured electric-field strength rather than phantom dosimetry, and both appear in modest journals, so they corroborate the low-dose reading without settling it.

Numerical dosimetry that models the in-ear geometry of a Bluetooth earbud in an anatomically realistic head is largely absent from the peer-reviewed literature. The closest analogues model cochlear implants: at 900 MHz a worst-case simulation found a maximum 10 g SAR of 1.31 W/kg near the implant electrode with a 0.33 °C temperature rise, a localized enhancement within thermal-safety bounds (McIntosh et al., 2008), and at 2.4 GHz, the Bluetooth and WLAN band, the presence of an implant produced only localized point-SAR differences near the electrode array and negligible change in averaged SAR in the cochlea and head (Parazzini et al., 2010). What the child-dosimetry literature adds is that tissue-specific absorption in children's heads differs from adults' because of thinner skull and pinna, higher tissue conductivity and shorter source-to-target distances, a result established for handset-at-the-ear geometries (Christ et al., 2010; Gandhi et al., 2012; Fernández-Rodríguez et al., 2015) that does not transfer directly to earbuds, which transmit at far lower power, but that does argue for child-specific phantoms in any future earbud dosimetry.

Comparison with medical devices is instructive. Bluetooth-enabled hearing aids and cochlear implant sound processors use the same low-power radios found in earbuds, with in-canal or behind-the-ear placement, and no adverse auditory effect from the radio component has been reported in the audiology literature. This is the strongest argument against the earbud concern on peak-exposure grounds. It does not address chronic exposure duration in a vulnerable population, because hearing-aid users are typically older adults with existing loss and cochlear-implant users have non-functional cochleae by definition, not teens with intact but vulnerable cochleae.

4.5 Why this profile is dosimetrically distinct

The correct framing is not that earbuds are small phones. It is that chronic in-ear exposure is a different profile on four dimensions: it is low-SAR (one to two orders of magnitude below a phone at the head), continuous (hours per day rather than minutes of calls), bilateral (both ears, both cochleae, both auditory nerves), and cochlea-adjacent (the source sits in the ear canal, 20 to 30 mm from the cochlea, rather than at the pinna). No published epidemiological study has characterized this profile, and none of the legacy phone studies can be read across to it. That is the empty intersection at the center of this review.

5. The acoustic-dose axis

5.1 WHO Make Listening Safe and global estimates

WHO states that over 1 billion young adults are at risk of permanent, avoidable hearing loss due to unsafe listening practices (World Health Organization, 2024a). Dillard et al. (2022), in a systematic review and meta-analysis of 33 studies covering 19,046 individuals with WHO co-authorship, estimated that 0.67 to 1.35 billion people aged 12 to 34 engage in unsafe listening, with pooled prevalence of unsafe personal-listening-device use of 23.81 percent and unsafe entertainment-venue exposure of 48.20 percent. WHO's Make Listening Safe initiative, launched in 2015, produced with ITU the safe listening device standard discussed in section 5.4 (World Health Organization & International Telecommunication Union, 2019).

5.2 Personal-listening-device levels and durations in adolescents

Measured output levels from personal listening devices range from about 75 dB(A) at typical settings to over 100 dB(A) at maximum, and teens in noisy environments raise volume to overcome background noise (Portnuff et al., 2011). Portnuff (2016) reviewed the evidence and concluded that a minority of young users listen at levels that exceed occupational damage-risk criteria, but that the proportion is large enough in absolute terms to constitute a public-health problem. In Europe, EN 50332 limits the default output of personal music players to 85 dB(A) with a user-overridable maximum of 100 dB(A) (CENELEC, 2013), a limit that predates TWS earbuds and applies to the player rather than the earbud.

5.3 Noise-induced synaptopathy mechanisms

Section 3.3 described the outcome; the mechanism is glutamate excitotoxicity at the inner-hair-cell ribbon synapse. Sustained loud sound drives inner hair cells to release glutamate at rates that swell and destroy the postsynaptic terminals of the auditory nerve fibers, particularly the low-spontaneous-rate fibers that carry the highest thresholds (Kujawa & Liberman, 2009; Furman et al., 2013). ROS generation in the organ of Corti amplifies and prolongs the damage (Henderson et al., 2006). The lesion is silent on the audiogram but visible in ABR wave I amplitude in animals and, contentiously, in humans (Bramhall et al., 2019). Adolescents accumulate this lesion from personal listening at doses that never produce a threshold shift.

5.4 ITU-T H.870 and the sound-allowance framework

ITU-T Recommendation H.870, Guidelines for safe listening devices/systems, was first approved in 2018 and revised to version 2 in March 2022, co-developed with WHO under Make Listening Safe (ITU-T, 2022). It defines two modes. Mode 1, for adults, sets a weekly sound allowance of 1.6 Pa^2h, equivalent to 80 dB(A) for 40 hours. Mode 2, for sensitive users including children, sets 0.51 Pa^2h, equivalent to 75 dB(A) for 40 hours. The allowance uses a 3 dB exchange rate, so 83 dB(A) consumes the adult allowance in 20 hours, 86 dB(A) in 10 hours, 89 dB(A)

in 5 hours. Devices conforming to the standard track cumulative dose and warn the user. The standard is the world's reference for the acoustic output of the exact devices at issue in this review. It contains no provision for the RF-EMF the same devices emit.

5.5 The additive problem: same device, same hours, two exposures

Because TWS earbuds deliver acoustic dose and RF-EMF from the same device at the same time, the two exposures are physically inseparable in real-world use. The population receiving the highest personal-audio acoustic dose is the same population receiving the highest chronic in-ear RF-EMF dose, over the same hours, through the same developmental window. Any epidemiological design that measures one and not the other will attribute to the measured exposure whatever effect the unmeasured one contributes. That is a reason for an exposome-first design that records both, not an argument that the RF-EMF contribution is large.

6. Proposed mechanisms of non-thermal RF-EMF interaction with the auditory system

International exposure guidelines are built on established thermal effects: tissue heating from RF absorption, with limits set to keep temperature rise below levels that cause harm (ICNIRP, 2020). The mechanisms below are proposed for exposures too weak to heat tissue measurably. None is accepted by ICNIRP or WHO as established; several are supported by animal and in vitro evidence of uneven quality; all are contested. They are presented so that the empty intersection can be read in mechanistic terms.

6.1 Oxidative stress and ROS in cochlear tissue

The most-cited non-thermal mechanism is oxidative stress. Yakymenko et al. (2016) reviewed 100 studies of low-intensity RF-EMF and reported that 93 found evidence of oxidative effects in biological systems; the review's authors sit in the precautionary community and its inclusion criteria were not systematic, but the volume of positive reports is not trivial. ICNIRP's response is that oxidative-stress findings at sub-thermal exposure are inconsistent, often lack adequate dosimetry, and have not been linked to adverse health outcomes (ICNIRP, 2020). For the cochlea specifically, the hypothesis is that RF-EMF adds to the ROS burden already generated by acoustic dose, accelerating the synaptic and strial damage described in section 3.7. Animal studies that report auditory-pathway oxidative or apoptotic markers after RF exposure are reviewed in section 7.

6.2 Voltage-gated calcium channels

Pall (2013) proposed that RF-EMF activates voltage-gated calcium channels, raising intracellular calcium and driving downstream nitric oxide and peroxynitrite production. The hypothesis has been influential in the precautionary literature and is part of the ICBE-EMF mechanistic case (ICBE-EMF, 2022). It is contested by

reviewers who argue that the fields induced in tissue by sub-thermal RF-EMF are far too weak to gate these channels and that well-characterized exposures in the 2.4 GHz band show no consistent biological effect (Foster & Moulder, 2013). For the cochlea, calcium homeostasis is central to hair-cell function and synaptic release, so the hypothesis has a target; whether the trigger exists at earbud field strengths is disputed and untested.

6.3 Blood-labyrinth and blood-brain barrier

The cochlea is protected by a blood-labyrinth barrier analogous to the blood-brain barrier. RF-EMF effects on blood-brain-barrier permeability were reported in rodents by Salford et al. (2003) and have been contested by non-replication (McQuade et al., 2009). No study has examined blood-labyrinth-barrier permeability under RF-EMF. The stria vascularis, which generates the endocochlear potential, is the tissue most sensitive to barrier disruption, and Gao et al. (2024) showed that strial hyperpermeability is the first cochlear event after ionizing radiation. This pathway is plausible in outline and untested in substance.

6.4 Schwann-cell and auditory-nerve lineage: the schwannoma signal

The strongest RF-EMF animal finding relevant to the auditory nerve is oncological. The NTP (2018a) reported clear evidence of malignant heart schwannoma in male rats exposed to whole-body 900 MHz GSM and CDMA RF at 1.5 to 6.0 W/kg. The Ramazzini Institute reported a significant increase in heart schwannoma in male rats exposed lifelong to 1.8 GHz GSM at 50 V/m, a base-station environmental level far below the NTP exposures (Falcioni et al., 2018). Schwann cells myelinate the auditory nerve, and vestibular schwannoma (acoustic neuroma) is the tumor on which the IARC Group 2B classification partly rests (International Agency for Research on Cancer, 2013). Two independent bioassays producing tumors of the same cell lineage at different exposure levels is the reason the auditory nerve enters the discussion. It is a carcinogenesis endpoint, not a tinnitus endpoint, and the human acoustic-neuroma epidemiology is mixed (section 8.2).

6.5 Thermal versus non-thermal: what ICNIRP accepts and disputes

ICNIRP (2020) accepts that RF-EMF above guideline levels causes tissue heating and, at high enough exposure, nerve stimulation and thermal damage. It does not accept that any non-thermal biological effect has been demonstrated to cause adverse health outcomes below guideline levels, and its guidelines therefore contain no non-thermal restriction. ICBE-EMF (2022) argues that the guidelines rest on 1980s behavioral studies in five monkeys and eight rats with safety factors applied to a 4 W/kg threshold, and that the subsequent evidence on oxidative stress, DNA damage and the NTP and Ramazzini tumors invalidates the thermal-only assumption. The two positions are irreconcilable at present, and this review does not adjudicate between them. It notes that the ICNIRP framework is what authorizes unrestricted earbud exposure, and that the framework was not built with chronic in-canal sources in mind.

7. In vitro and animal evidence on RF-EMF and the auditory system

7.1 Otoacoustic emissions and ABR studies

The functional animal literature is the closest thing to a direct test of RF-EMF on cochlear physiology, and it is mixed.

Table 3. Animal studies of RF-EMF exposure and auditory function or structure.

Study	Species	Frequency and exposure	Outcome measure	Finding
Aran et al. (2004)	Guinea pig	900 MHz GSM, 1 to 4 W/kg, 1 h/day, 2 months	DPOAE, ABR, histology	No effect
Galloni et al. (2005a, 2005b)	Rat	900 and 1800 MHz GSM, 2 W/kg local SAR in the ear, 2 h/day, 4 weeks	DPOAE	No effect
Galloni et al. (2009)	Rat	UMTS (2 GHz band), 4 weeks	DPOAE	No effect
Budak et al. (2009)	Rabbit	1800 MHz GSM-like, 15 min/day, 7 days, infants versus adults	DPOAE	Amplitudes increased in exposed infants and decreased in exposed adults; authors attributed both to ear-canal temperature; no SAR dosimetry
Kaprana et al. (2011)	Rabbit	900 MHz GSM simulator, 60 min acute	ABR	Delayed waves III to V and prolonged interpeak latencies during exposure
Kaprana et al. (2021)	Rabbit	1800 MHz GSM, short-term	ABR	Latency prolongation ipsilateral to the source after more than 30 min; contralateral ear unchanged
Kayabasoglu et al. (2011)	Rat	900 and 1800 MHz phones, 1 h/day, 30 days, newborn and adult	DPOAE	No effect
Özgür et al. (2015)	Rat	900 MHz, 1 h/day, 30 days	Histology, apoptosis markers	Degeneration in auditory-pathway neurons
Çeliker et al. (2017)	Rat	2100 MHz GSM-like, 6 h/day, 30 days	ABR, histology, apoptosis markers	ABR unchanged; neuronal degeneration and raised apoptotic index; melatonin protective
Er et al. (2020)	Rat	900 MHz, acute and chronic	ABR, oxidative markers	Chronic exposure altered ABR alongside lipid-peroxidation and antioxidant changes

The pattern is consistent enough to summarize. Well-controlled functional studies with characterized dosimetry (Aran et al., 2004; Galloni et al., 2005a, 2005b, 2009; Kayabasoglu et al., 2011) report no effect on outer-hair-cell function or auditory thresholds at exposures around or above guideline limits. Histological studies from a single Turkish research group (Özgür et al., 2015; Çeliker et al., 2017) report auditory-pathway neuronal degeneration and apoptosis markers after chronic exposure, with antioxidant protection. The rabbit studies report ABR latency prolongation during acute exposure at 900 MHz (Kaprana et al., 2011) and, ipsilaterally only, at 1800 MHz (Kaprana et al., 2021), and age-dependent DPOAE changes after short daily exposure without SAR dosimetry, which the authors attributed to ear-canal heating (Budak et al., 2009). A more recent rat study reported chronic 900 MHz exposure altering ABR together with oxidative-stress markers (Er et al., 2020), which is the one functional positive with a redox readout. The functional null studies are methodologically stronger; the positive histological studies are the ones that engage the oxidative-stress mechanism.

7.2 Histology and apoptosis studies

The Turkish studies deserve specific attention because they are the positive animal evidence. Özgür et al. (2015) exposed rats to 900 MHz for one hour daily over 30 days and reported degeneration and apoptotic markers in auditory-pathway neurons. Çeliker et al. (2017) used 2100 MHz for six hours daily over 30 days and reported similar histological findings with protection by melatonin, while ABR was unchanged, so the study is null on function and positive on structure. The 2100 MHz study is the closest in frequency to the 2.4 GHz Bluetooth band. Both studies have limitations typical of the field: exposure characterized by field strength rather than measured SAR, no functional hearing endpoint, single laboratory, and outcomes assessed by histology that is sensitive to fixation and handling. They constitute partial support for biological plausibility, not demonstration.

7.3 Antioxidant-protection studies

Where positive effects are reported, antioxidants attenuate them: melatonin in Çeliker et al. (2017), and, in the broader RF-EMF literature, melatonin, N-acetylcysteine and others in tissues from brain to testis (Yakymenko et al., 2016). That pattern is what one would expect if the effect were ROS-mediated. It is also what one would expect if the effect were a handling or restraint-stress artifact, since antioxidants blunt stress responses generally. The specificity of the antioxidant protection to RF-EMF has not been tested with sham-exposure controls adequate to distinguish the two.

7.4 The NTP and Ramazzini bioassays

The NTP studies (2018a, 2018b) exposed rats and mice to 900 MHz (rats) and 1900 MHz (mice) GSM and CDMA RF for nine hours daily over two years at whole-body SAR of 1.5, 3 and 6 W/kg. In male rats there was clear evidence of malignant heart schwannoma and some evidence of malignant glioma and adrenal pheochromocytoma; female rats and mice showed equivocal or no evidence. The exposures exceed regulatory limits by design, as is standard in bioassays. Falcioni et al. (2018) at the Ramazzini Institute exposed

Sprague-Dawley rats from prenatal life to natural death to 1.8 GHz GSM at 5, 25 and 50 V/m for 19 hours daily and found a statistically significant increase in heart schwannoma in males at 50 V/m, an exposure comparable to base-station environmental levels and roughly a thousandfold below the NTP SAR. The convergence of two independent bioassays on the same rare tumor of the same cell lineage is the single most substantial RF-EMF animal finding, and it concerns the cell type that myelinates the auditory nerve.

7.5 Quality assessment and dosimetry limitations

The animal literature on RF-EMF and hearing is small, old, and uneven. The functional null studies date from 2004 to 2011 and used GSM and UMTS bands; none used 2.4 GHz Bluetooth modulation. The positive histological studies lack SAR dosimetry. No study modeled chronic in-canal exposure, and none combined RF-EMF with noise, which is the exposure that teenagers actually receive. A systematic review of RF-EMF and the auditory system with formal risk-of-bias assessment does not exist. The two closest syntheses are a narrative review of audiovestibular symptoms after exposure to acoustic and electromagnetic energy outside conventional hearing, which found RF-EMF linked to auditory and vestibular dysfunction in animal models with older, poorly quantified human evidence (Lubner et al., 2020), and a systematic review of RF-EMF effects on children and adolescents that rated the body of evidence low to inadequate (Bodewein et al., 2022). The WHO-commissioned series addressed tinnitus and sleep as symptoms but not hearing function as an endpoint. The honest summary is that the animal evidence is biologically plausible and partially supported for oxidative-stress pathways, contested in functional assays, and silent on the exposure of interest.

8. Human evidence on RF-EMF and hearing or tinnitus

8.1 Provocation and short-term exposure studies

A cluster of studies in the 2000s exposed volunteers to mobile-phone RF and measured immediate auditory effects. Parazzini et al. (2005) found no effect of 10-minute GSM exposure on DPOAE. The European GUARD project found no effect of GSM exposure on hearing across several laboratories (Parazzini et al., 2007). Oysu et al. (2005) found no effect on ABR after 15-minute exposure. Uloziene et al. (2005) found no effect on DPOAE or thresholds after 10 minutes. Kwon et al. (2010) found no effect on ABR in a double-blind design. Kellenyi et al. (1999) reported a small ABR latency shift after 15-minute GSM exposure, Ozturan et al. (2002) found no effect on transient-evoked otoacoustic emissions, and Sievert et al. (2005) found no acute effect on cochlear or brainstem function. These are acute studies of phone-to-ear exposure; they establish that a single short exposure does not measurably change cochlear or brainstem function, which is unsurprising, and they say nothing about chronic exposure.

8.2 Case-control and cross-sectional studies

Hutter et al. (2010), in an Austrian matched case-control study, reported an odds ratio of 1.95 (95 percent CI 1.00 to 3.80) for tinnitus with ipsilateral mobile-phone use of four years or longer. Panda et al. (2010), in India, found that long-term mobile-phone users had worse extended-high-frequency thresholds and DPOAE in the dominant ear, and Velayutham et al. (2014) reported high-frequency loss in heavy users. These positive cross-sectional findings share the limitations of self-reported exposure and reverse-causation risk, since users with early hearing symptoms may attend more to phone use. On acoustic neuroma, the Interphone study found no overall association but a raised odds ratio in the highest decile of cumulative call time (INTERPHONE Study Group, 2011); the Swedish Hardell group reported increased risk with long-term mobile and cordless (DECT) phone use in a pooled case-control analysis of 316 cases (Hardell et al., 2013); and a large Swedish case-control study found no association (Pettersson et al., 2014). The acoustic-neuroma epidemiology is genuinely mixed and is why IARC retains the 2B classification under active re-evaluation.

8.3 The COSMOS cohort

The Cohort Study of Mobile Phone Use and Health recruited 21,049 participants in Sweden and 3,120 in Finland between 2007 and 2013, with operator-recorded call time and four-year follow-up (Auvinen et al., 2019). No association was found between baseline call time and tinnitus or hearing loss, with or without adjustment for noise exposure. It is the strongest single dataset on legacy phone use and tinnitus, and it recruited before TWS earbuds existed.

8.4 The WHO-commissioned systematic review and its critique

Röösli et al. (2024), the second of the WHO-commissioned RF-EMF systematic reviews, synthesized 13 eligible papers on tinnitus, migraine and non-specific symptoms and concluded that RF-EMF below guideline values does not cause these outcomes, while rating the evidence very low certainty for few studies, risk of bias, inconsistency, indirectness and imprecision. Frank, Melnick and Moskowitz (2025) published a critical appraisal challenging the exposure assessment and certainty grading and calling for retraction. ARPANSA (2024) endorses the review series. The dispute is reported here, not adjudicated. What both sides agree on is that every included study measured phone call time.

8.5 Bluetooth-specific human studies

Two human studies have examined Bluetooth headset fields on hearing. Balachandran et al. (2012) exposed 30 volunteers to a Bluetooth headset and found no significant short-term change in pure-tone audiometry or DPOAE. Mandalà et al. (2014) recorded compound action potentials directly from the exposed auditory nerve during surgery while a mobile phone or a Bluetooth headset was placed near the ear; the phone decreased compound action potential amplitude and increased latency, while the Bluetooth headset produced no significant

short-term effect. Both are acute and small. No published study has tested chronic TWS earbud use against tinnitus incidence, thresholds or otoacoustic emissions in any population.

It must be stated plainly that no human study to date isolates the radiofrequency component of wireless-earbud use from its acoustic component. Studies associating earbud or earphone use with tinnitus or subclinical otoacoustic-emission change, including the adolescent series in section 3, attribute the effect to sound-pressure exposure and did not measure RF-EMF. The chronic in-ear wireless-RF hypothesis therefore remains untested in humans and is presented in this review as a candidate mechanism, not as a demonstrated one.

8.6 Hearing aids and cochlear implants with Bluetooth

Bluetooth-enabled hearing aids and cochlear implant processors have been in use for over a decade, with the same low-power radios found in earbuds and with in-canal or behind-the-ear placement. The audiology literature reports no adverse auditory effect attributable to the radio, and dosimetric modeling of cochlear implants at 900 MHz and at 2.4 GHz shows only localized point-SAR enhancement near the electrode array with negligible change in averaged head SAR (McIntosh et al., 2008; Parazzini et al., 2010). This is the most reassuring real-world data on chronic in-canal Bluetooth exposure. Its limitation is population: hearing-aid users are typically older adults with existing sensorineural loss, cochlear-implant users have non-functional cochleae by definition, and neither group's outcomes speak to an intact teenage cochlea's vulnerability to an additional oxidative or synaptic load. No study has looked for tinnitus onset or change in hearing-aid users as a function of Bluetooth streaming hours.

8.7 Electromagnetic hypersensitivity and tinnitus

Tinnitus is among the most commonly reported symptoms in people who attribute symptoms to EMF (Landgrebe et al., 2008; Baliatsas et al., 2012). Double-blind provocation studies have repeatedly failed to show that EHS individuals can detect fields or that symptoms track true exposure rather than perceived exposure (Rubin et al., 2010). Landgrebe et al. (2008) found that EHS subjects showed altered cortical excitability on transcranial magnetic stimulation, suggesting a real central-nervous-system difference in the group regardless of the field-detection question. EUROPAEM lists tinnitus among EMF-attributed symptoms and names Bluetooth and DECT among sources for exposure-history review (Belyaev et al., 2016). The EHS literature establishes that a tinnitus-prone subgroup exists that attributes its symptoms to EMF; it does not establish that EMF causes the symptoms.

8.8 The exposure-misclassification problem

Every element of the human null evidence, from the provocation studies to COSMOS to the WHO review, measured phone-to-ear call time. That exposure is intermittent, unilateral, high-SAR and pinna-adjacent. The exposure of interest is continuous, bilateral, low-SAR and canal-resident. If chronic low-level exposure matters through cumulative oxidative or synaptic load rather than through peak absorption, the legacy studies were not

designed to detect it. If it does not matter, the legacy studies cannot show that either, because they did not measure it. The null is accurate for the exposure it measured and silent on the exposure of interest.

9. Convergence: the two axes system by system

Table 4. Convergence between teenage tinnitus physiology, acoustic dose and RF-EMF.

Auditory system feature	Altered in teenage tinnitus	Perturbed by acoustic dose	Perturbed by RF-EMF (evidence and strength)	Convergence rating
Inner-hair-cell synapses	Synaptopathy at normal thresholds (Liberman et al., 2016)	Established mechanism (Kujawa & Liberman, 2009)	Untested; no RF-EMF synaptic-count study exists	Plausible, untested
Outer-hair-cell function (DPOAE)	Normal in São Paulo adolescents (Sanchez et al., 2016)	Reduced at high doses	Null in well-controlled rodent studies (Galloni et al., 2005a, 2009); altered in rabbits without dosimetry (Budak et al., 2009)	Weak, mixed
Stria vascularis and blood-labyrinth barrier	Not directly studied in adolescents	ROS-mediated strial damage (Henderson et al., 2006)	Untested for RF-EMF; analogous strial damage under ionizing radiation (Gao et al., 2024)	Plausible, untested
Cochlear oxidative stress	Inferred from noise mechanisms	Established (Henderson et al., 2006; Fetoni et al., 2019)	Reported in auditory pathway after chronic exposure, single group (Özgür et al., 2015; Çeliker et al., 2017); contested	Plausible, partially supported
Auditory nerve and Schwann cells	Spiral ganglion degeneration follows synaptopathy	Established	Schwannoma in two bioassays (NTP, 2018a; Falcioni et al., 2018); acute CAP change with phone, less with headset (Mandalà et al., 2014); ABR latency delay in rabbits (Kaprana et al., 2011)	Plausible for lineage vulnerability, untested for tinnitus
Central gain and sound-level tolerance	Reduced LDL is the discriminating variable (Sanchez et al., 2016)	Established consequence of peripheral loss	Untested	Untested
Sleep and stress physiology	Sleep disturbance and stress are top correlates (Rhee et al., 2020; Kim, 2018)	Indirect	Reproducible EEG sleep-spindle changes under RF-EMF (section 10)	Plausible, supported for sleep
Calcium signaling	Central to hair-cell and synaptic function	Excitotoxic calcium entry	VGCC hypothesis (Pall, 2013) contested (Foster & Moulder, 2013)	Weak

The convergence is strongest for oxidative stress and sleep, weakest for outer-hair-cell function and calcium signaling, and untested for the synapse, which is the lesion that matters most in adolescents. That distribution

defines the research agenda: the first study to fund is a synaptic-count study under chronic RF-EMF with and without noise.

10. Sleep and stress as candidate mediating pathways

Sleep is the one physiological domain in which sub-thermal RF-EMF has a reproducible human signal. Pulse-modulated RF-EMF before sleep alters sleep EEG, particularly spindle-frequency power in non-REM sleep, in double-blind crossover studies (Loughran et al., 2005; Regel et al., 2007; Schmid et al., 2012; Lustenberger et al., 2013). Danker-Hopfe et al. (2016) found no consistent effect of GSM and UMTS exposure on polysomnographic sleep quality in a large study, but the laboratory spindle finding has replicated across groups. The effect is small and its clinical meaning is unknown; ICNIRP treats it as not established as harmful.

The relevance to tinnitus runs through section 3.6: sleep loss lowers the threshold for phantom perception, raises distress, and is among the strongest correlates of teenage tinnitus (Rhee et al., 2020; Crönlein et al., 2016). Nighttime earbud use, whether for sleep sounds, white noise or content, is a growing behavior in adolescents and places a Bluetooth radio in both ear canals during the hours when RF-EMF has its one reproducible physiological effect and when acoustic dose would otherwise be zero. No study has examined nighttime earbud use, sleep architecture and tinnitus together. This is a candidate mediating pathway, not a demonstrated one, and it is the second study to fund.

11. Regulatory and institutional positions

WHO maintains that no adverse health effects have been established from exposure below ICNIRP guideline limits, and its public Q&A does not address tinnitus specifically (World Health Organization, 2024b). ICNIRP's 2020 guidelines contain thermal restrictions only (ICNIRP, 2020). IARC classified RF-EMF as Group 2B in 2011 on limited evidence for glioma and acoustic neuroma (International Agency for Research on Cancer, 2013; Baan et al., 2011) and, following its 2024 advisory group, designated RF-EMF a high priority for re-evaluation in the 2025 to 2029 cycle (Berrington de González et al., 2024); as of September 2026 no new classification had been published. The WHO-commissioned cancer review found moderate-certainty evidence that mobile-phone use likely does not increase brain-cancer risk (Karipidis et al., 2024), a finding ICBE-EMF has contested (ICBE-EMF, 2024). ARPANSA endorses the WHO series (ARPANSA, 2024).

ANSES has recommended limiting the population's exposure to radiofrequencies, especially for children and intensive users (ANSES, 2019a), has called for moderate and supervised use of wireless technologies by children after finding possible effects on well-being and cognition and no conclusion possible on auditory function

(ANSES, 2016), and has recommended that older phones with high trunk SAR no longer expose users when carried close to the body (ANSES, 2019b). On 5G, ANSES concluded that deployment in the 3.5 GHz band is unlikely to present new health risks, that data for 26 GHz are insufficient, and that research and exposure monitoring should continue (ANSES, 2021). France requires SAR labeling and, under the 2015 Abeille law, restricts Wi-Fi in nurseries. No ANSES opinion addresses TWS earbuds.

In the United States, the D.C. Circuit in *Environmental Health Trust v. FCC* (2021) found the FCC's decision to retain its 1996 RF exposure limits arbitrary and capricious for failing to address evidence on children, long-term exposure and non-cancer effects, and remanded for a reasoned explanation. Five years later the FCC had not complied. Petitioners filed for a writ of mandamus on 18 May 2026, and on 26 August 2026 the D.C. Circuit ordered the FCC to explain its non-compliance within 30 days (Environmental Health Trust, 2026), so the agency's explanation was due as this review went to press. The regulatory basis for unrestricted consumer wireless exposure in the United States therefore rests on limits a federal court has found inadequately justified.

ITU-T H.870 governs acoustic output and is silent on RF-EMF (ITU-T, 2022). EUROPAEM's clinical guideline names tinnitus among EMF-related symptoms and Bluetooth among sources for exposure-history review (Belyaev et al., 2016). ICBE-EMF (2022) challenges the thermal-only framework. The EMF Scientist Appeal reported 268 signatory scientists from 45 nations as of May 2025 (International EMF Scientist Appeal, 2025); the 5G Appeal reported 438 scientists and physicians as of July 2024 (5G Appeal, 2024).

Table 5. Stakeholder map.

Organization or programme	Country / region	Position on RF-EMF, Bluetooth exposure and tinnitus
World Health Organization	International	Skeptical or neutral; no established effects below ICNIRP limits; tinnitus not addressed
ICNIRP	International	Skeptical; thermal restrictions only
ARPANSA	Australia	Skeptical; endorses WHO systematic reviews
COSMOS Study Group	Sweden, Finland, UK, IARC	Skeptical; null for call time and tinnitus
Swiss TPH / Röösli et al.	Switzerland / international	Skeptical, very low certainty; contested by Frank et al. (2025)
Karipidis et al.	Australia / international	Skeptical on cancer; contested by ICBE-EMF (2024)
IARC Monographs	International	Cautious; Group 2B; high priority for re-evaluation 2025 to 2029
ANSES	France	Cautious; precautionary on children and body-worn phones; no new risk found for 5G at 3.5 GHz; no TWS opinion
NTP / NIEHS	United States	Cautious; clear evidence of heart schwannoma in male rats

Organization or programme	Country / region	Position on RF-EMF, Bluetooth exposure and tinnitus
Ramazzini Institute	Italy	Cautious; schwannoma at environmental exposure
Medical University of Vienna	Austria	Cautiously supportive of a prolonged-use signal
Universidade de São Paulo	Brazil	Cautious; identified the adolescent phenotype; precautionary on susceptible individuals
Recep Tayyip Erdoğan University group	Turkey	Precautionary; positive chronic-exposure rat histology
ICBE-EMF	International	Precautionary; limits do not protect against non-thermal effects
EMF Scientist Appeal (268 scientists, 45 nations)	International	Precautionary
5G Appeal (438 signatories)	International, EU-focused	Precautionary; moratorium on 5G
EUROPAEM	European Union	Precautionary clinical guideline; names tinnitus and Bluetooth
BioInitiative Working Group	International	Actively concerned; advocacy synthesis
Environmental Health Trust	United States	Actively concerned; petitioner in EHT v. FCC
Physicians for Safe Technology	United States	Actively concerned; Bluetooth resource page
ITU-T H.870 / WHO Make Listening Safe	International	Silent on RF-EMF; regulates acoustic dose only
NIDCD, CDC/NIOSH, AAP, ASHA, ATA, HHF	United States	Silent on RF-EMF as a tinnitus risk factor

12. Public and advocacy discourse

The earbud-safety question entered public discourse in March 2019 when a British tabloid reported that 250 scientists had signed a petition warning that AirPods could cause cancer, and the story was syndicated widely. The article conflated the 2015 International EMF Scientist Appeal, which concerns EMF exposure generally and does not mention AirPods or Bluetooth, with the product. Fact-checkers documented the conflation, quoting a signatory that the appeal does not specify any product (Palma, 2019; Full Fact, 2022). The episode matters because it shaped both sides: it gave advocacy outlets a viral frame and gave skeptical outlets a debunk to cite, and neither engaged the actual question, which is chronic exposure in a vulnerable population.

Environmental Health Trust maintains pages on wireless earbud safety and recommends wired alternatives for children, framing its position around the 2021 court ruling and the child-dosimetry literature. Physicians for Safe

Technology maintains a Bluetooth hazards page that reports power classes and SAR filings and correctly states that no long-term human study exists (Physicians for Safe Technology, 2024). The BioInitiative Report (BioInitiative Working Group, 2012) foregrounds acoustic neuroma among the outcomes associated with phone use. On the skeptical side, consumer-technology media and science-communication outlets respond with the dosimetry: earbud SAR is a small fraction of phone SAR, which is itself below limits, and Bluetooth hearing aids have shown no harm. Both responses are accurate as far as they go, and neither addresses the empty intersection. The public discourse has been a debate about peak exposure when the scientific question is about chronic exposure in a developing auditory system.

13. Evidence gaps and research agenda

13.1 Limitations of this review

This is a narrative review with structured verification, not a systematic review; it carries no PRISMA protocol or formal risk-of-bias scoring. Market and shipment figures are commercial estimates. Bluetooth SAR figures rest on manufacturer filings read through secondary reports, two low-rigor broadband-field studies, and cochlear-implant simulations used as analogues, not on independent phantom dosimetry of earbuds. The cochlear redox mechanism is drawn in part from an ionizing-radiation analogy. The positive animal histology comes from one research group. The observed increase in cases that motivates the review comes from clinical and professional experience within EFEIA's network and has not yet been quantified in a repeated population survey; the review says so where it matters and does not present the observation as a measured trend. Every reference was resolved at the primary level before publication, and figures that could not be located in their sources were left out rather than repeated. Most decisively, no human study of chronic TWS exposure and tinnitus exists, so the central hypothesis remains untested rather than supported or refuted.

13.2 Research agenda

Seven priorities. The first responds to the observed increase itself; the rest are ordered by the convergence analysis in section 9.

- **A repeated teenage tinnitus surveillance series with a fixed case definition.** Annual or biennial school-based surveys in at least two countries, using the same questionnaire, the same booth-verification protocol and the same loudness-discomfort measure each wave, with wear time of in-ear wireless devices recorded from the first wave. This is the study that would turn the increase EFEIA observes in practice into a measured population trend, and it costs little relative to what it settles.
- **A synaptic-count animal study under chronic RF-EMF with and without noise.** Expose young rodents to 2.4 GHz Bluetooth-modulated RF at earbud-representative SAR for 8 hours daily over 8 weeks,

with and without moderate noise, and count inner-hair-cell ribbon synapses by confocal immunohistochemistry alongside ABR wave I amplitude and strial permeability. This tests the lesion that matters in teens at the exposure that adolescents receive.

- **A prospective teenage cohort with dual dosimetry.** Recruit 2,000 adolescents aged 12 to 15, fit in-ear acoustic dosimeters and worn RF exposimeters for repeated one-week windows, record TWS wear time and laterality from device logs, and pre-register tinnitus, loudness discomfort levels, extended-high-frequency thresholds and speech-in-noise as outcomes at two and four years.
- **A nighttime-earbud sleep study.** Crossover design in adolescents who sleep with earbuds: active Bluetooth versus sham-paired devices, polysomnography with spindle analysis, and morning tinnitus rating.
- **An RF annex to ITU-T H.870.** Petition ITU-T Study Group 16 and WHO Make Listening Safe to add an RF-EMF characterization requirement for safe listening devices, on par with the acoustic sound-allowance framework.
- **An exposome-first tinnitus registry.** A clinical registry that records acoustic dose, personal-wireless wear time, ambient RF-EMF and susceptibility markers including EHS phenotype at first visit, following the EUROPAEM exposure-history framework, so that competing hypotheses can be tested in the same patients.
- **Independent Bluetooth earbud dosimetry.** Peer-reviewed SAR and field-strength measurement of current TWS models in child and adolescent head phantoms, at the cochlea and auditory nerve, during Classic A2DP and LE Audio streaming.

13.3 Contingent triggers

If the IARC re-evaluation raises RF-EMF above Group 2B, or if the synaptic-count study returns a positive result, or if a TWS-dominated cohort replicates the Hutter et al. (2010) signal, the posture recommended here should escalate from precautionary monitoring to active advisory. If the synaptic-count study and a well-powered TWS cohort both return nulls, the RF-EMF axis can be de-prioritized relative to the acoustic axis, which would remain the established target.

14. Conclusion

As of September 2026, chronic in-ear Bluetooth exposure is a real, novel, rapidly growing environmental exposure that has not been tested against tinnitus in humans. The acoustic-dose axis is established, quantified and regulated. **The RF-EMF axis is different in kind: the human epidemiology is null but was designed for a different exposure; the mechanistic evidence is plausible for oxidative stress and the Schwann-cell lineage, contested for cochlear function, and untested for the synapse; and the dosimetry shows earbuds are not phones without showing that continuous bilateral canal-resident exposure is inert in a developing cochlea already carrying invisible noise damage.**

The strongest claims in both directions outrun the data. "Earbuds cause tinnitus" is unsupported. "Earbuds are proven safe with respect to tinnitus" is equally unsupported, because the relevant study has not been done. An Environmental Physiology reading treats chronic in-ear Bluetooth exposure as a complementary environmental toxin candidate alongside cumulative acoustic dose: plausible via the redox and Schwann-cell pathways, named in the EHS clinical literature, and structurally unaddressed by the standard that governs the acoustic output of the same device. **The honest posture is exposome-first, mechanism-aware, precautionary until the direct epidemiology exists, and unwilling to treat the absence of studies on the actual exposure profile as evidence of the safety of that profile.**

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