The association between radiofrequency radiation and audiovestibular dysfunction: A scoping review

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Abstract

Background: Radiofrequency radiation (RFR) technology has become ubiquitous. To date, literature of the bioeffects of RFR at nonthermal levels has mainly focused on the nervous system, whereas the audiovestibular system has not had much of the spotlight. Given the increasing utilization of RFR technology and reports of possible RFR-caused auditory symptoms, a crucial need exists to clarify the association between RFR and audiovestibular dysfunction and explore their potential mechanisms.

Objective: The objective of this scoping review is to investigate the biophysical and cellular effects of RFR on the audiovestibular system and identify gaps in knowledge for future research.

Methods: Guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews were followed. Any study investigating the clinical manifestations or mechanisms of RFR on the audiovestibular system in humans, animals, or theoretical models were considered eligible.

Results: 147 studies met eligibility. The investigation of cell phones accounts for the majority of RFR-auditory studies. The pattern of results shows that duration of exposure from cell phones may be a contributing factor in the manifestation of adverse symptoms. RFR effects at the cellular level revealed histologic changes possibly due to increased oxidative stress, alterations in the neurotransmitter system, decrease in neurotrophic factors, and alterations in blood circulation and microglia in the auditory cortex. There is no convincing evidence of vestibular dysfunction due to RFR exposure.

Conclusion There is stronger evidence to support that RFR causes adverse bioeffects on the auditory system with excessive exposure as a contributing factor. RFR's effects at the cellular level may be the cause for these physical manifestations. However, definitive conclusions at this time

are limited due to the small number of studies investigating the exact pathogenesis of RFR on the audiovestibular system and the narrow use of RFR sources.

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Introduction

Radiofrequency radiation (RFR) is part of the electromagnetic spectrum (Fig 1), consisting of radio waves and microwaves in the frequency range of 3 kilohertz (kHz) to 300 gigahertz (300 GHz) (1). Despite RFR's beneficial utility in telecommunication devices, radar, industrial heating and sealing, microwave ovens, and various military applications (2), the bioeffects of RFR has been up for debate since the beginning of its discovery. Whereas the thermal effects of microwaves have been well accepted in the scientific community, the potential organic effects at nonthermal levels remain questionable (3, 4), especially given RFR is a form of nonionizing radiation (1). However, since the early 1930s, some scientists have recognized RFR at nonthermal levels have physiologic effects on various body systems with the central nervous system being the most sensitive (3). Although not conclusive, subsequent research on the nervous system have suggested nonthermal RFR may be genotoxic (5-9), alter membrane channels (10-13), modify neurotransmitter systems (14-17), change the structure of the blood brain barrier (5, 18, 19), and even impair learning and memory (20, 21). Despite being closely related in proximity and structure to the nervous system, the auditory and vestibular systems have not been given much of the spotlight. Given the ubiquity of RFR emitting devices in modern society and the fact that RFR could be used as a potential weapon as evidenced by the recent events in Havana, Cuba on US diplomats (22), there is a crucial need to clarify the effects of RFR on the audiovestibular system.

Fig 1. Electromagnetic Spectrum. The electromagnetic spectrum with specific examples of RFR emitting devices and their respective frequencies

The objective of this scoping review is to systematically investigate the potential biophysical and cellular effects of RFR exposure on the audiovestibular system and identify existing gaps in knowledge for future research. Specifically, the adverse clinical manifestations, including hearing loss, tinnitus, vertigo, and nystagmus will be the focus along with any possible damage at the microscopic level and mechanisms of injury.

Materials and Methods

A protocol was drafted using the Joanna Briggs Institute Manual for Evidence Synthesis-Development of the Scoping Review Protocol (23), which was revised by the research team. The protocol can be accessed upon request from one of the team members. The scoping review methods were developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).

Any study investigating the clinical manifestations or mechanisms of RFR on the audiovestibular system in humans or animals were considered. Studies that evaluated adverse audiovestibular effects due to RFR, including hearing loss, tinnitus, vertigo, and nystagmus were of considerable interest. No publication dates or publication status restrictions were imposed. Studies investigating the association between RFR and cancer were excluded as this disease process was not in accordance with the purpose of this scoping review. In addition, any articles meeting the following conditions were excluded from this study: review articles, scoping reviews, systematic reviews, meta-analysis, editorials, commentaries, abstracts, letters, and non-English full text articles.

Studies were identified by searching electronic databases by a single author (ML). An English language filter was used while no date limits were applied. This search was conducted in PubMed (1971-Present), Scopus (1971-Present), Cochrane Library (1988-Present), and Web of Science (1980-Present). All databases were queried on March 17, 2021. The following search terms were used in different combinations: *radiofrequency radiation, microwaves, electromagnetic field, auditory dysfunction, hearing loss, tinnitus, vertigo, nystagmus, vestibular system*. After duplicate articles were removed with EndNote, Rayyan QCRI (24) was used to screen the articles by titles, abstracts, and full text in three subsequent stages by two independent authors (ML, WZ). The two screeners were blinded to the other person's decision at every stage. Any disagreements between the two screeners by the end of full text screening were discussed between the two screeners and resolved. A data charting form was created by one author (ML) and verified by a second author (WZ). The tool created allowed capture of relevant information on study characteristics and outcomes of interest. Data was extracted from the included studies by one author (ML), which was then confirmed for accuracy and completeness by a second author (WZ).

Information extracted from each study included: 1) type of study (auditory, vestibular, or both), 2) study population (human or animal), 3) RFR source, 4) duration of RFR exposure (chronic or acute), 5) RFR frequency used, and 6) outcomes of RFR exposure, including effects on various auditory or vestibular function parameters, cellular effects, and clinical manifestations. The studies were separated into 2 groups: auditory effects and vestibular effects. Within these two groups, the studies were then divided based on study population (human, animal, model), RFR source, study type, duration of exposure, and outcomes. If a systematic review, meta-analysis, review article, or scoping review was identified, the sources were reviewed to ensure none were missed.

Results

A total of 2821 articles were identified through PubMed, Scopus, Cochrane Library, and Web of Science. After duplicates were removed, 1819 articles remained. Based on the titles and abstracts, 1599 articles were excluded with 220 full text articles to be retrieved and assessed for eligibility. Of the full text articles, 73 were excluded for the following reasons: 24 were either a review article, scoping review, systematic review, or meta-analysis; 12 were not about radiofrequency radiation; 19 did not investigate the audiovestibular system, 3 were about vestibular schwannomas, 3 were letters, 5 were abstracts, 3 were commentaries, and 1 was a non-English full text article. Three articles were excluded because the full text articles could not be obtained. The remaining 147 articles were considered eligible for this review. The results of the literature search and screening are summarized in Fig 2.

Fig 2. Literature Search. PRISMA flow diagram.

The characteristics and results of individual sources of evidence are presented in supporting information. To summarize, the studies investigated RFR's effects on the auditory system, vestibular system, or both. Three types of study populations were used: humans, animals, or models. Some studies used cell lines from various animal species to investigate the microscopic effects of RFR. The majority of studies used cell phones as the RFR source although others were used, such as radio broadcasting stations, WiFi, Bluetooth, radar, and various microwave generators. Duration of exposure to RFR was simplified to either acute (< 1 month) or chronic (≥ 1 month). To investigate the adverse RFR effects on the audiovestibular system, the studies were of two types: 1) experimental, where objective audiologic, vestibular, or cellular testing was conducted after RFR exposure or 2) survey studies where subjects self-reported various audiovestibular symptoms. The various audiologic testing parameters used are defined in Table 1.

Table 1. Definitions of Audiologic Testing

Audiologic Test	Definition
Pure tone audiometry (PTA)	

	Assesses air-conduction and bone-conduction thresholds of hearing at different frequencies (25).
Otoacoustic emissions (OAEs)	Two types: 1) Transient otoacoustic emissions (TEOAE) and 2) Distortion product otoacoustic emissions (DPOAE). Both assess the health of the inner ear, specifically the outer hair cells (25).
Auditory evoked potentials (AEPs)	Assesses the nerves in the auditory system in response to a sound stimulus (25). Different types of AEPs include auditory brainstem response (ABR), also known as brainstem response audiometry (BERA) or brainstem auditory evoked response audiometry (BAER); middle latency response (MLR); and mismatch negativity (MMN) (26).
Event related potentials (ERPs)	Electrical responses generated by the brain in response to an event or stimuli. It can be used to assess cognitive status and certain brain functions such as attention, memory, and language (26).

Of the 147 eligible studies, 135 studies focused on the auditory effects, 12 pertained to vestibular effects, and 6 studies looked at both the auditory and vestibular effects of RFR. Of the auditory studies, 33 investigated microwave hearing while 108 evaluated the adverse auditory bioeffects. Out of the 108 studies that evaluated the adverse auditory effects of RFR, 74 were human studies, 32 were animal studies, and 2 were theoretical model studies. All vestibular studies investigated adverse effects. Nine of the vestibular studies used humans while 3 used theoretical models. Fig 3 summarizes the various audiovestibular bioeffects due to RFR exposure and will serve as a model for the following narrative.

Fig 3. Bioeffects of RFR on the Audiovestibular System. The various physical and cellular effects of RFR on the auditory and vestibular systems are outlined in the diagram.

1. Auditory Bioeffects of RFR

1.1 Microwave Hearing

Aside from tissue heating, the most widely accepted bioeffect of RFR is the phenomenon of hearing short pulses of modulated microwave radiation by humans and laboratory animals (27-29). These RFR sounds are reported as a buzz, click, hiss, or knock that originates from within or near the back of head when irradiated with microwaves (27). Many studies have been done on the mechanism of microwave hearing (30-40). Currently, the accepted mechanism is the thermoelastic theory (30, 41-43). This theory states microwave pulses are absorbed by the soft tissues in the head which launch a thermoelastic wave of acoustic pressure and travels by bone conduction to the inner ear where cochlear receptors are activated through the same process involved in normal acoustic hearing (30). Microwave hearing is not known to cause adverse auditory effects; however, this requires further investigation.

1.2 Adverse Auditory Bioeffects of RFR

The adverse auditory bioeffects of RFR can manifest as symptoms, such as hearing loss or tinnitus; alterations in auditory testing parameters (Table 1); or damage at the cellular level. We quantified the studies investigating adverse effects of RFR on the auditory and vestibular systems based on the presence or absence of the aforementioned adverse bioeffects, the frequency of RFR, and exposure duration. Fig 4 accounts for 114 studies of the original 147. Studies that pertained to microwave hearing or did not provide a specific RFR frequency were excluded from Fig 4. As shown, the majority of studies investigated the frequency range of 800-2100 MHz due to cell phone exposure. Within this frequency range, one can conclude that chronic exposure (≥ 1 month) to RFR in the 800-2100 MHz frequency may be associated with the presence of adverse auditory effects while acute exposure (< 1 month) may not be associated with adverse effects. Unfortunately, due to the paucity of data in the frequency range < 800 MHz and > 2100 MHz, a definitive conclusion is difficult to make at the moment.

Fig 4. Studies on Adverse Auditory and Vestibular Bioeffect of RFR. This chart quantifies the studies investigating the adverse audiovestibular effects of RFR exposure by frequency and exposure duration. The circle size and number pertain to the number of studies that fit within each respective combination of presence/absence of bioeffects, RFR frequency, and exposure duration.

With the presence of clinical manifestations of auditory dysfunction after RFR exposure, damage at the cellular level is to be expected. Studies using electron microscopy and histopathologic analysis has revealed signs of apoptosis and degeneration in auditory hair cells and the cochlear nucleus (44-48). Although one may think the thermal effects of RFR are to blame for this cellular damage, Schmid et al, through several theoretical model experiments, has concluded that temperature related biological effects on the inner ear from cell phone exposure is unlikely

(49, 50). Thus, a nonthermal mechanism of RFR affecting different cellular functions is a possibility. Per Fig 3, some of these mechanisms to cellular damage and auditory dysfunction could be due to RFR's ability to alter the neurotransmitter system (51, 52), increase oxidative stress (48, 53), decrease neurotrophic factors (54), and alter the blood circulation and microglia in the auditory cortex (55, 56). For example, after exposing mice to 835 MHz RFR for 3 months, the glycine receptor immunoreactivity and glycine receptor immunoreactive neurons were found to be decreased in the cochlear nuclear complex. It was concluded that this downregulation of glycine release, a major inhibitory neurotransmitter, may result in cochlear damage (51). In addition, after exposing rats to 1800 MHz RFR for 24 hours, the reactive oxygen species were found to be increased in the cochlear stria marginal cells (53). In another study by Maskey et al, brain-derived neurotrophic factor and glial-derived neurotrophic factor were found to be decreased in the nuclei of the superior olivary complex, an important nuclei along the auditory brainstem. Without these neurotrophic factors, maintenance of cellular function and integrity in the auditory brainstem may be compromised, leading to adverse clinical symptoms (54). Finally, in the auditory cortex, it was found that intermittent exposure to cell phones caused short-term and medium-term alterations in blood circulation (55) while 1800 MHz RFR exposure caused morphological change and reduced spontaneous firing of microglia, an important cell of the brain involved in immunological functions (56).

2. Vestibular Bioeffects

The main vestibular symptom associated with RFR exposure is vertigo. In the 1970s Lebovitz postulated that microwave irradiation could create thermal gradients within the semicircular canals of the vestibular apparatus, thus causing vestibular stimulation (57-59). Despite this theory, vestibular stimulation by RFR seems to be non-conclusive as evidenced by Fig 4. For instance, two survey studies showed a significant association between cell phone exposure and self-reported vertigo (60, 61). However, three survey studies do not (62-64). Moreover, studies using video nystagmography did not find any evidence of vestibular stimulation after acute cell phone exposure (65, 66). Furthermore, a study assessing cell phone's effects on horizontal and vertical perception of the user showed no significant effects (67). Given the paucity of studies in this area, an exact conclusion cannot be made at this time.

Discussion

In 2016, U.S. diplomats in Havana, Cuba began experiencing neurological and audiovestibular symptoms after hearing a sound that was described as loud, high frequency, and localized (68). Subsequent evaluation of the affected personnel found otolithic abnormalities and evidence of cognitive dysfunction (68). Despite the early controversy that surrounded the etiology to these peculiar symptoms, recently the National Academies of Sciences, Engineering, and Medicine has independently concluded that the symptoms experienced by the U.S. diplomats were consistent with those from pulsed RFR (22). This is not the first time RFR has been used as a potential weapon on U.S. personnel. During the 1950s to 1970s, the U.S. embassy in Moscow was irradiated with microwaves by the Soviets believing that RFR at nonthermal levels had adverse effects (69). To this date, much research has been done on the neurological bioeffects of RFR. However, given RFR's potential as a weapon and ubiquitous use in everyday life, understanding its consequences on the audiovestibular system is crucial.

This scoping review aims to uncover the association between RFR and the resulting audiovestibular symptoms. Our search revealed 147 studies on this topic, including those on the well-studied microwave hearing phenomenon to the adverse effects on the auditory and vestibular systems. Unfortunately, compared to the nervous system, the studies on the audiovestibular system are mainly limited to those from cell phone exposure with a limited number of studies investigating other sources of RFR. From the pattern of results, the duration of exposure to cell phones was shown to be a factor in causing adverse auditory effects. Not surprisingly, the cellular effects and mechanisms of RFR on the audiovestibular system seem to closely mimic those observed for the nervous system, including alterations to the neurotransmitter system and increase oxidative damage.

Although called different names in the past, such as microwave sickness (70) or neurasthenia (71), the syndrome of adverse clinical effects due to RFR exposure is currently known as electromagnetic hypersensitivity (72). Unfortunately, like RFR's effects on the human body, much is still left to be discovered. Future research should focus on the mechanism and pathogenesis of RFR's effects on the audiovestibular system, which can lead to proper diagnosis, management, and treatment for those who present with symptoms. In addition, RFR sources other than cell phones need more attention as evidenced by newer technology and the recent events in Havana, Cuba.

This scoping review has several limitations. First, because the majority of studies used cell phones as the RFR source, not much can be concluded for other RFR producing devices. Second, given the heterogeneity in the data and experimental protocols, comparison between studies was difficult to do. As such, only generalized conclusions could be made. And last, given the paucity of studies for RFR effects on the vestibular system, no definitive conclusion can be made at this time.

Conclusions

There is stronger evidence to support that RFR causes a possible adverse bioeffect on the audiovestibular system with duration of exposure as a possible important factor contributing to clinical symptoms, such as hearing loss, tinnitus, and vertigo. Despite studies showing similar mechanisms of cellular damage to that found for the nervous system, more needs to be done in terms of finding the exact pathogenesis and broadening the RFR source used.

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Supporting information

S1 Table. Characteristics and Results of Individual Studies

First author, date, reference	Country	Study Category (auditory, vestibular, both)	Study population (Sample size)	RFR Source/ Frequency	Duration exposure (acute/ chronic)*	Auditory/ Vestibular Parameters of interest	Adverse effects on audiovestibular parameters? (or main findings)
Al-Dousary 2007(73)	Saudi Arabia	Auditory	Human (1)	Cell phone (N/A	Chronic	PTA	Case report- Sensorineural hearing loss due to cell phone
Alsanosi 2013(74)	Saudi Arabia	Auditory	Human (60)	Cell phone (850-1900 MHz)	Acute	PTA, DPOAE	Yes
Arai 2003(75)	Japan	Auditory	Human (15)	Cell phone (800 MHz)	Acute	ABR, MLR	No
Aran 2004(76)	France	Auditory	Animal (Guinea pigs-48)	Cell phone (900 MHz)	Acute and chronic	DPOAE, ABR, light microscopy	No
Bak 2003(77)	Poland	Auditory	Human (45)	Cell phone (435-1800 MHz)	Acute	ABR	No
Balachandran 2012(78)	Malaysia	Auditory	Human (30)	Bluetooth (2.4-2.5 GHz)	Acute	PTA, DPOAE	No
Balikci 2005(79)	Turkey	Auditory	Human (695)	Cell phone (900-1800 MHz)	Chronic	Self-reported symptoms (clicking in ears)	Yes

Bamiou 2008(66)	UK	Both	Human (30)	Cell phone (882 MHz)	Acute	TEOAE, videooculography	No
Bamiou 2015(67)	UK	Vestibular	Human (30)	Cell phone (882 MHz)	Acute	Vertical and horizontal perception	No
Bhagat 2016(80)	India	Auditory	Human (40)	Cell phone (800-2000 MHz)	Chronic	PTA, BERA	No
Budak 2009(81)	Turkey	Auditory	Animal (Rabbits-36)	Cell phone (1800 MHz)	Acute	DPOAE	Yes
Budak 2009(82)	Turkey	Auditory	Animal (Rabbits-36)	Cell phone (1800 MHz)	Acute	DPOAE	Yes
Budak 2009(83)	Turkey	Auditory	Animal (Rabbits-36)	Cell phone (1800 MHz)	Acute	DPOAE	Yes
Budak 2009(84)	Turkey	Auditory	Animal (Rabbits-36)	Cell phone (1800 MHz)	Acute	DPOAE	Yes
Cain 1978(85)	U.S.	Auditory (Microwave Hearing)	Human (8) Animals (Cat, dog, chinchilla-N/A)	Microwave generator (3.0 GHz)	Acute	Auditory evoked responses	Determined microwave hearing threshold parameters for different mammals
Celiker 2017(47)	Turkey	Auditory	Animal (Rats-14)	Cell phone (2100 MHz)	Chronic	ABR, histopathologic/	No difference in ABR. Histopathologic/ immunohistochemical analysis of cochlear

						immunohistochemical analysis of cochlear nuclei	nuclei showed increased degeneration.
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Chou 1975(33)	U.S.	Auditory (Microwave Hearing)	Animal (Guinea pigs-5)	Microwave generator (918 MHz)	Acute	Cochlear microphonic	Microwave auditory effect is accompanied by mechanical disturbance of cochlear hair cells
Chou 1979(86)	U.S.	Auditory (Microwave Hearing)	Animal (Guinea pigs-10)	Microwave generator (918 MHz)	Acute	Middle ear contribution to microwave hearing effect	Middle ear not crucial for microwave hearing
Chou 1979(43)	U.S.	Auditory (Microwave Hearing)	Animal (Guinea pigs-N/A)	Microwave generator (918 MHz)	Acute	Threshold of microwave hearing via auditory brainstem evoked responses	Threshold to microwave hearing related to energy per pulse for short pulses and peak power for longer pulses. Evidence in agreement with thermoelastic theory.
Chou 1976(34)	U.S.	Auditory (Microwave Hearing)	Animal (Cat-N/A)	Microwave generator (918 MHz)	Acute	Cochlear microphonics	Describes characteristics of cochlear

							microphonics in cats
Chou 1985(41)	U.S.	Auditory (Microwave Hearing)	Animal (Rat-10)	Microwave generator (2450 MHz)	Acute	Brainstem evoked response	Rat responses to microwave pulses consistent with thermoelastic theory.
Cinel 2007(87)	UK	Auditory	Human (168)	Cell phone (888 MHz)	Acute	Auditory order threshold task	No
Clemens 2012(88)	Germany	Auditory (Microwave Hearing)	Theoretical human model	Model (High power microwave)	N/A	Numerical dosimetry simulation	Models predict possible microwave hearing from high power microwaves and MRIs
Colletti 2011(89)	Italy	Auditory	Human (with Meniere's disease) (7)	Cell phone (900 MHz)	Acute	ABR, CNAP	Yes
Curcio 2004(90)	Italy	Auditory	Human (20)	Cell phone (902 MHz)	Acute	Acoustic simple reaction time test, acoustic choice-reaction time test, tympanic membrane temperature	Improvement of reaction times and increase in tympanic temperature under cell phone exposure

Das 2017(91)	India	Auditory	Human (82)	Cell phone (900-1800 MHz)	Chronic	PTA	Yes
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Davidson 2007(63)	UK	Both	Human (117)	Cell phone (N/A)	Chronic	Self-reported symptoms (hearing tinnitus, balance)	No
De Seze 2001(92)	France	Auditory	Human (30)	Cell phone (900 MHz)	Acute	AEP, CDAS	No
Er 2020(48)	Turkey	Auditory	Animal (Rats-60)	Cell phone (900 MHz)	Acute and chronic	ABR, lipid peroxidation and antioxidant status	Adverse effects in acute exposure but no adverse effects in chronic exposure
Foster 1974(30)	U.S.	Auditory (Microwave Hearing)	Model (Water filled tank)	Microwave generator (2450 MHz)	Acute	Pressure transients caused by microwave pulses	Proposal of thermoacoustic expansion theory of microwave hearing
Frei 2012(93)	Switzerland	Auditory	Human (1375)	Mobile phone base stations, broadcast transmitters, cell phone	Chronic	Self-reported symptoms (Tinnitus)	No
Frey 1961(27)	U.S.	Auditory (Microwave Hearing)	Human (4)	2 RFR transmitters (1310 MHz, 2982 MHz)	Acute	Perception of microwave hearing	First experimental report of microwave hearing

Frey 1979(94)	U.S.	Auditory (Microwave Hearing)	Animal (Rats-10; Guinea pigs-16)	RFR transmitter (1.1-1.2 GHz)	Acute	Dynamic time-averaged interferometric holography to assess motion of hair, skin, muscle, bone, and brain during RFR exposure	Results suggest against thermoacoustic expansion theory of microwave hearing.
Frey 1985(95)	U.S.	Auditory (Microwave Hearing)	Human (3)	Triode cavity oscillator (1.2 GHz)	Acute	Determine if repetition pitch phenomenon is a characteristic of microwave hearing	Results indicate that microwave hearing mechanism only involves portion of cochlea.
Frey 1973(29)	U.S.	Auditory (Microwave Hearing)	Human (4)	Pulse signal source (1.245 GHz)	Acute	Perception of sound from ultra-high frequency RFR	Perceived loudness of RFR sound is a function of peak. power
Galloni 2009(96)	Italy	Auditory	Animal (Rats-48)	Cell phone (1946 MHz)	Chronic	DPOAE	No
Galloni 2005(97)	Italy	Auditory	Animal (Rats-58)	Cell phone (900 MHz)	Acute and chronic	DPOAE	No
Galloni 2005(98)	Italy	Auditory	Animal (Rats-48)	Cell phone (900 and 1800 MHz)	Chronic	DPOAE	No
Garcia Callejo 2005(99)	Spain	Auditory	Human (323)	Cell phone (900-1800 MHz)	Chronic	PTA	Yes

Goiceanu 2011(100)	Romania	Auditory	Human (49)	Radar	Chronic	Investigated international standards of pulsed microwaves in radar equipment in Romania	Exposure was below that for thermal effects; however, peak power density exceeded limits and correlated to adverse effects.
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Golomb 2018(101)	U.S.	Auditory	Human (N/A)	RFR Source	Chronic	Assess whether symptoms (i.e., hearing noises, tinnitus) experienced by U.S. diplomats in Havana, Cuba consistent with RFR exposure	Symptoms reported by U.S. diplomats consistent with RFR exposure
Grisanti 1998(102)	Italy	Auditory	Human (25)	Cell phone (897.5 MHz)	Acute	DPOAE, TEOAE	No
Gupta 2015(103)	India	Auditory	Human (100)	Cell phone (900-1800 MHz)	Chronic	ABR	No
Guy 1975(32)	U.S.	Auditory (Microwave Hearing)	Human (2); Animal (Cat-N/A)	Microwave generator (2450 MHz)	Acute	Threshold of microwave hearing, locus of action, and consistency with thermoacoustic theory	Results consistent with thermoacoustic expansion theory
Hamblin 2006(104)	Australia	Auditory	Human (120)	Cell phone (895 MHz)	Acute	Auditory event related potential, reaction time	No

Hidisoglu 2018(105)	Turkey	Auditory	Rats (36)	RFR treatment (2.1 GHz)	Acute	AEP, lipid peroxidation, reactive astrogliosis, nitric oxide synthase enzymes	Results show significant change in AEPs and reduced oxidative damage
Hillert 2008(64)	Sweden	Vestibular	Human (71)	Cell phone (884 MHz)	Acute	Self-reported symptoms (vertigo)	No
Huang 2008(106)	South Korea	Auditory	Animal (Immortalized mouse auditory hair cells)	Cell phone (1763 MHz)	Acute	Changes in cell cycle, DNA damage, stress response, gene expression	No
Hutter 2010(107)	Austria	Auditory	Human (100)	Cell phone (N/A)	Chronic	Self-reported symptom (Tinnitus)	Yes (for prolonged use; ≥ 4 years)
Jadia 2019(108)	India	Auditory	Human (500)	Cell phone (800-2000 MHz)	Chronic	PTA	Yes
Janssen 2005(109)	Germany	Auditory	Human (28)	Cell phone (900 MHz)	Acute	DPOAE	No
Joines 1981(110)	U.S.	Auditory (Microwave Hearing)	Theoretical Model	N/A	N/A	Mechanism of microwave hearing	Possible mechanism is the generation of field-induced forces that divide materials of different electrical properties
Kacprzyk 2020(111)	Poland	Auditory	Human (23)	Cell phone (2100 MHz)	Acute	TEOAE	No

Kaprana 2011(112)	Greece	Auditory	Animal (Rabbits-30)	Cell phone (900 MHz)	Acute	ABR	Yes
Kayabasoglu 2011(113)	Turkey	Auditory	Animal (Rats-40)	Cell phone (900 and 1800 MHz)	Chronic	DPOAE	No
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Kellenyi 1999(114)	Hungary	Auditory	Human (10)	Cell phone (N/A)	Acute	ABR	Yes
Kerekhan-janarong 2005(115)	Thailand	Auditory	Human (98)	Cell phone (800-900 MHz)	Chronic	PTA, TEOAE, DPOAE, ABR	No
Khan 2008(116)	Saudi Arabia	Auditory	Human (286)	Cell phone (N/A)	Chronic	Self-reported symptom (hearing problem)	Yes
Khullar 2013(117)	India	Auditory	Human (60)	Cell phone (900-2000 MHz)	Chronic	ABR	Yes
Kim 2019(52)	South Korea	Auditory	Animal (Rats-8)	RFR generator (1850 MHz)	Acute	ABR, sPSCs, transmission electron microscopy	No change in ABR or morphological change; however, sPSCs were increased

Kizilay 2003(118)	Turkey	Auditory	Animal (Rats-18)	Cell phone (900 MHz)	Chronic	DPOAE	No
Kleinlogel 2008(119)	Switzerland	Auditory	Human (15)	Cell phone (1950 and 900 MHz)	Acute	AEP, Auditory Evoked P300	No
Kothari 2020(120)	India	Auditory	Human (50)	Cell phone (900-1800 MHz)	Chronic	BERA	Yes
Kucer 2014(60)	Turkey	Both	Human (350)	Cell phone, computer (N/A)	Chronic	Self-reported symptoms (hearing loss, tinnitus, vertigo)	Yes
Kumar 2018(121)	India	Auditory	Human (190)	Cell phone (800-2000 MHz)	Chronic	DPOAE	Yes
Kwon 2010(122)	Finland	Auditory	Human (17)	Cell phone (902 MHz)	Acute	Auditory event related potentials, mismatch negativity	No
Kwon 2010(123)	Finland	Auditory	Human (17)	Cell phone (902 MHz)	Acute	ABR	No
Kwon 2009(124)	Finland	Auditory	Human (17)	Cell phone (902 MHz)	Acute	Mismatch negativity	No
Lamech 2014(125)	Australia	Auditory	Human (92)	Smart meters (N/A)	Chronic	Self-reported symptoms (Tinnitus)	Yes

Landgrebe 2009(126)	Austria	Auditory	Human (89)	Cell phone (N/A)	Chronic	Self-reported symptoms (Tinnitus)	No
Lebovitz 1973(57)	U.S.	Vestibular	Theoretical Model	N/A	N/A	Investigate the mechanism of microwave induced vestibular stimulation	Propose theory of vestibular stimulation by microwaves via caloric stimulation
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Lebovitz 1973(58)	U.S.	Vestibular	Theoretical Model	N/A	N/A	Investigate the mechanism of microwave induced vestibular stimulation	Propose theory of vestibular stimulation by microwaves via caloric stimulation
Lebovitz 1999(59)	U.S.	Vestibular	Theoretical Model	N/A	N/A	Investigate the mechanism of microwave induced vestibular stimulation	Propose theory of vestibular stimulation by microwaves via caloric stimulation
Lebovitz 1977(39)	U.S.	Auditory (Microwave Hearing)	Animal (Cats-N/A)	Microwave generator (915 MHz)	Acute	Investigate single auditory neuron response to pulsed microwaves	Results support thermoacoustic expansion theory

Lebovitz 1977(40)	U.S.	Auditory (Microwave Hearing)	Animal (Cats-N/A)	Microwave generator (915 MHz)	Acute	Investigate single auditory neuron response to pulsed microwaves	Results support thermoacoustic expansion theory
Lin 1976(35)	U.S.	Auditory (Microwave Hearing)	Theoretical Model	N/A	N/A	Compares 3 possible mechanisms of microwave hearing	Concludes that thermoacoustic expansion theory is most likely
Lin 1976(36)	U.S.	Auditory (Microwave Hearing)	Theoretical Model	N/A	N/A	Investigates where transduction of microwave hearing occurs	Concludes that thermoacoustic expansion theory is most likely
Lin 1977(37)	U.S.	Auditory (Microwave Hearing)	Theoretical Model	N/A	N/A	Theoretical model of acoustic signal generated in the heads of humans and animals irradiated with microwave pulses	Results show that frequency of auditory signals depends on function of size and properties of head. Agreement with thermoacoustic expansion theory.
Lin 1977(38)	U.S.	Auditory (Microwave Hearing)	Theoretical Model	N/A	N/A	Investigate whether a theoretical model is in agreement with previous experimental results on microwave hearing	Results show that theoretical model is in agreement with previous experiments and thermoacoustic theory.
Lin 1979(127)	U.S.	Auditory (Microwave Hearing)	Animal (Cats-12)	Microwave generator (2450 MHz)	Acute	Investigate whether microwave evoked auditory responses are similar to those	Auditory responses from microwaves and acoustic stimuli are similar

						produced by acoustic pulses	
Lin 2010(128)	U.S.	Auditory (Microwave Hearing)	Theoretical model	N/A	N/A	Investigate microwave hearing caused by MRI	Present pressure distributions and specific absorption rates inside human head during MRI exposure
Maby 2004(129)	France	Auditory	Human (28)	Cell phone (N/A)	Acute	AEP	Yes
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Maghbooli 2020(130)	Iran	Auditory	Human (96)	Cell phone (N/A)	Chronic	ABR, PTA	Yes
Mandala 2014(131)	Italy	Auditory	Human w/ (Meniere's disease-12)	Bluetooth (2.4 GHz)	Acute	CNAP	No
Marino 2000(132)	Italy	Auditory	Animal (Rats-8)	Horn antenna (940 MHz)	Acute	DPOAE	No
Maskey 2014(51)	South Korea	Auditory	Animal (Mice-20)	Cell phone (835 MHz)	Chronic	ABR, glycine receptor immunoreactivity, immunohistochemistry	Yes
Maskey 2014(54)	South Korea	Auditory	Animal (Mice-10)	Cell phone (835 MHz)	Chronic	Distribution of neurotrophic factors in nuclei of superior olivary complex	Yes

McNamee 2016(133)	Canada	Auditory	Animal (Mice-20)	RFR generator (1.9 GHz)	Acute	Gene expression in auditory cortex	No
Meo 2005(134)	Saudi Arabia	Auditory	Human (437)	Cell phones (900-1800 MHz)	Chronic	Self-reported symptoms (hearing loss)	Yes
Meric 2009(135)	Turkey	Auditory	Human (25)	Radio Broadcasting Station (1062 kHz)	Chronic	BERA, PTA	No
Meric 1998(136)	Turkey	Auditory	Human (61)	Radio Broadcasting Station (1062 kHz, 98.4 MHz, 88.4 MHz, 95.5 MHz	Chronic	PTA	Yes
Monnery 2004(137)	UK	Auditory	Human (12)	Cell phone (N/A)	Acute	DPOAE, TEOAE	No
Mora 2006(138)	Italy	Auditory	Human (20)	Cell phone (900-1800 MHz)	Acute	TEOAE, ABR	No
Morales 2009(139)	Spain	Auditory	Animal (Guinea pigs-34)	Transverse electromagnetic wave guide (4000, 5000 Hz)	Chronic	Otoacoustic emissions, scanning electron microscopy	No
Mortazavi 2007(62)	Iran	Both	Human (518)	Cell phones (N/A)	Chronic	Self-reported symptoms (tinnitus, vertigo)	No

Movahedi 2017(140)	Iran	Auditory	Human (70)	Mobile phone jammers (N/A)	Acute	PTA	Yes
Occelli 2018(56)	France	Auditory	Animal (Rats exposed to LPs-29)	Cell phone (1800 MHz)	Acute	Immunodetection of Iba1(microglial marker) and electrophysiological recordings in auditory cortex	Results show that in neuroinflammatory conditions, RFR can affect auditory perception
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Oktay 2006(141)	Turkey	Auditory	Human (60)	Cell phone (900-1800 MHz)	Chronic	BERA, PTA	Yes
Oktay 2004(142)	Turkey	Auditory	Human (28)	Radio Broadcasting Stations (1062 kHz)	Chronic	BERA, PTA	Yes
Olsen 1981(42)	U.S.	Auditory (Microwave Hearing)	Theoretical Model (Head)	Microwave generator (1.10 GHz)	Acute	Measurement of acoustic pressures in head model by pulsed microwaves	Results agree with thermoacoustic expansion theory
Oysu 2005(143)	Turkey	Auditory	Human (18)	Cell phone (900 MHz)	Acute	ABR	No

Ozgur 2015(45)	Turkey	Auditory	Animal (Rats-12)	Cell phone (1800 MHz)	Chronic	ABR, histopathologic and immune-histochemical analysis of cochlear nuclei	ABR was not significantly affected but cochlear nuclei showed signs of degeneration
Ozturan 2002(144)	Turkey	Auditory	Human (30)	Cell phone (900 MHz)	Acute	TEOAE, DPOAE	No
Paglialonga 2007(145)	Italy	Auditory	Human (27)	Cell phone (900-1800 MHz)	Acute	TEOAE	No
Panda 2010(146)	India	Auditory	Human (162)	Cell phone (N/A)	Chronic	PTA, DPOAE, ABR, MLR	Yes
Panda 2011(147)	India	Auditory	Human (183)	Cell phone (N/A)	Chronic	PTA, DPOAE, ABR, MLR	Yes
Parazzini 2005(148)	Italy	Auditory	Human (15)	Cell phone (900, 1800 MHz)	Acute	DPOAE	No
Parazzini 2007(149)	Europe (multicenter)	Auditory	Human (169)	Cell phone (900, 1800 MHz)	Acute	PTA, TEOAE, DPOAE, ABR	No
Parazzini 2004(150)	Italy	Auditory	Animal (Rats-48)	Cell phone (900, 1800 MHz)	Chronic	DPOAE	No
Parazzini 2007(151)	Italy	Auditory	Animal (Rats-32)	Cell phone (900 MHz)	Chronic	DPOAE	No
Parazzini 2010(152)	Europe (multicenter)	Auditory	Human (73)	Cell phone (1947 MHz)	Acute	PTA, DPOAE, TEOAE, AEP	No

Parazzini 2009(153)	Europe (multicenter)	Auditory	Human (134)	Cell phone (1947 MHz)	Acute	PTA, DPOAE, TEOAE, AEP	No
Pau 2005(65)	Germany	Vestibular	Human (13)	Cell phone (889.6 MHz)	Acute	Video Nystagmography	No
Philip 2017(154)	India	Auditory	Human (150)	Cell phone (N/A)	Chronic	PTA, DPOAE	Yes
Ramya 2011(155)	India	Auditory	Human (50)	Cell phone (900-1800 MHz)	Chronic	PTA	Yes
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Redmayne 2013(156)	New Zealand	Auditory	Human (373)	Cell phone (30 MHz-5.8 GHz)	Chronic	Self-reported symptoms (Tinnitus)	Yes
Roschmann 1991(157)	Germany	Auditory (Microwave Hearing)	Human (6)	RF coils for MRI (2.4-170 MHz)	Acute	Studied microwave hearing with MRI coils	Results confirm thermoelastic theory
Sahoo 2011(158)	India	Auditory	Human (100)	Cell phone (N/A)	Chronic	PTA	Yes

Schmid 2007(49)	Austria	Auditory	Model (inner ear organs)	Cell phone (400, 900, 1850 MHz)	Acute	Temperature elevation in inner ear	RF induced temperature elevations were well below 1˚C; inner tissues were more affected by pulsed radiation
Schmid 2007(50)	Austria	Auditory	Model (middle and inner ear)	Cell phone (400-3700 MHz)	Acute	Temperature elevation in middle and inner ear	Results show that temperature related bioeffects unlikely
Seaman 1987(159)	U.S.	Auditory (Microwave Hearing)	Animal (Cat-3)	Microwave generator (915 MHz)	Acute	Studied microwave hearing in cats	Results consistent with prior studies
Seaman 1989(160)	U.S.	Auditory (Microwave Hearing)	Animal (Cat-18)	Diathermy applicator (915 MHz)	Acute	Response thresholds of cochlear neurons to microwave pulses determined	Microwave pulses stimulate cochlear nucleus units
Seckin 2014(44)	Turkey	Auditory	Animal (Rats-8)	Cell phone (900 and 1800 MHz)	Chronic	DPOAE, electron microscopy of cochlea	DPOAE showed no significant changes; electron microscopy of cochlea showed structural damage
Shayani-Nasab 2006(161)	Iran	Auditory	Human (200)	Cell phone (N/A)	Chronic	PTA	Yes
Sievert 2005(162)	Germany	Auditory	Human (12)	Cell phone (889.6 MHz)	Acute	ABR	No
Sommer 1964(28)	U.S.	Auditory (Microwave Hearing)	Human (N/A)	Electrostatic field	Acute	Investigate microwave hearing in electrostatic field	Electrostatic fields are responsible for microwave hearing

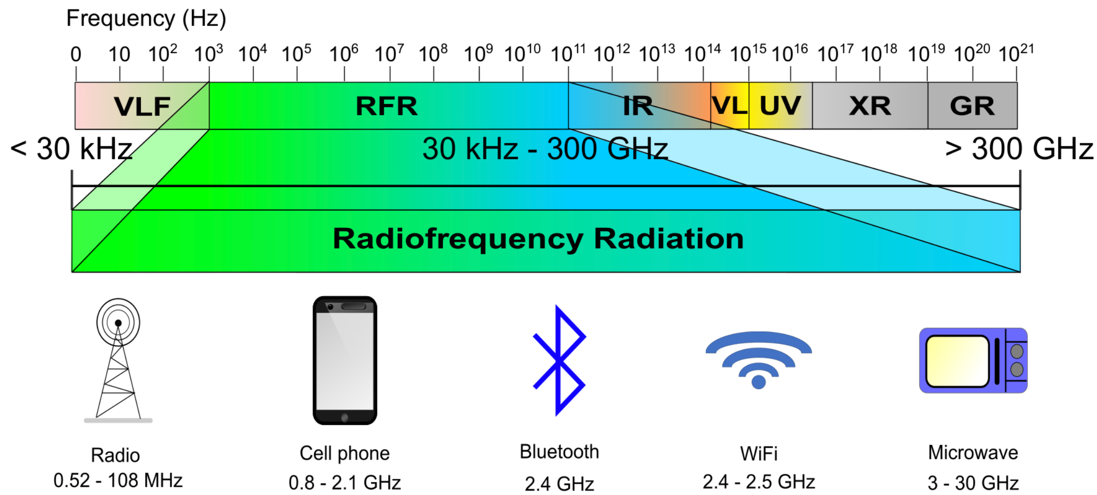
				generator (N/A)			
Spichtig 2012(55)	Switzerland	Auditory	Human (16)	Cell phone (900 MHz)	Acute	Effect of RFR on blood circulation in auditory region of brain	RFR exposure has short-term and medium-term effects on cerebral blood circulation and heart rate
Stefanics 2007(163)	Hungary	Auditory	Human (30)	Cell phone (900 MHz)	Acute	ABR	No
Stefanics 2008(164)	Hungary	Auditory	Human (36)	Cell phone (N/A)	Acute	Auditory event related potentials	No
Sudan 2013(165)	Denmark	Auditory	Human (52680)	Cell phone (N/A)	Chronic	Self-reported symptoms (hearing loss)	No
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Taylor 1974(31)	U.S.	Auditory (Microwave Hearing)	Animal (Cats-9)	Microwave generator (2450 MHz)	Acute	Establish locus of action of microwave hearing	Results show microwave hearing is mediated at periphery similar to acoustic hearing
Tyazhelov 1979(166)	Russia	Auditory (Microwave Hearing)	Human (N/A)	Microwave generator (800 MHz)	Acute	Investigate microwave hearing and thermoelastic theory	Thermoelastic theory may not totally correct

Uloziene 2005(167)	Lithuania	Auditory	Human (30)	Cell phone (900, 1800 MHz)	Acute	PTA, TEOAE	No
Uzwali 2012(168)	Nepal	Auditory	Human (30)	Cell phone (850, 1900 MHz)	Acute	ABR	Yes
Wachtel 1988(169)	U.S.	Auditory	Animal (Mice-N/A)	Microwave chamber (1250 MHz)	Acute	Investigate if microwave pulses can modify responses to other stimuli	Microwave pulses can suppress acoustic startle response in mice
Wilson 1985(170)	U.S.	Auditory (Microwave Hearing)	Animal (Cat-N/Ag)	Microwave generator (2450 MHz)	Acute	Investigate mechanism of microwave hearing	Results consistent with thermoelastic expansion theory
Wilson 1980(171)	U.S.	Auditory (Microwave Hearing)	Animal (Rats-11)	Microwave generator (918 MHz)	Acute	Identify site at which RFR acts in eliciting brain responses	Results show that auditory response to RFR acts on cochlea
Yang 2020(53)	China	Auditory	Animal (Rats-40)	Cell phone (1800 MHz)	Acute	DNA damage, cell apoptosis, and reactive oxygen species generation in cochlear cells	No increase in DNA damage or apoptosis; however, there was an increase in reactive oxygen species generation.
Yildiram 2013(172)	Turkey	Auditory	Animal (Rats-32)	Bluetooth (2400 MHz)	Chronic	DPOAE	No

Yitzhak 2009(173)	Israel	Auditory (Microwave Hearing)	Theoretical model	N/A	N/A	Evaluated amplitudes of sound waves generated in spherical head model by microwave pulses	Theoretical model of some previously described observations of microwave hearing
Yitzhak 2014(174)	Israel	Auditory (Microwave Hearing)	Theoretical model	N/A	N/A	Investigate pressure wave developing at cochlea	Pressure waves in cochlea follow a simple sinusoidal relation
Yorgancilar 2017(175)	Turkey	Auditory	Animal (Rats-16)	Wifi (2.4 GHz)	Chronic	DPOAE	Yes
Yorgancilar 2012(176)	Turkey	Auditory	Animal (Rats-14)	Cell phone (900 MHz)	Chronic	DPOAE	No
Youssef 2016(61)	Saudi Arabia	Both	Human (239)	Cell phone (N/A)	Chronic	Self-reported symptoms (Tinnitus, vertigo)	Yes
Yuasa 2006(177)	Japan	Auditory	Human (12)	Cell phone (800 MHz)	Acute	Somatosensory evoked potentials	No
First author, date, reference	**Country**	**Study Category (auditory, vestibular, both)**	**Study population (Sample size)**	**RFR Source/ Frequency**	**Duration exposure (acute/ chronic)***	**Auditory/ Vestibular Parameters of interest**	**Adverse effects on audiovestibular parameters? (or main findings)**
Zaret 1975(178)	U.S.	Both	Human (1)	Radar transmitter	Acute	Self-reported symptoms (deafness, vestibular dysfunction)	Case report of microwave worker who experienced bilateral deafness and vestibular dysfunction after acute exposure to intense microwaves

Zuo 2015(46)	China	Auditory	Animal (Rats-10)	Cell phone (1800 MHz)	Acute	DNA damage and autophagy markers in spiral ganglion neurons; transmission electron microscopy	No increase in DNA damage seen but caused cellular damage in already LPS induced cells.

Fig 1.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VLF
RFR
IR
VL
UV
XR
GR
< 30 kHz
30 kHz - 300 GHz
> 300 GHz
Radiofrequency Radiation
Radio
0.52 - 108 MHz
Cell phone
0.8 - 2.1 GHz
Bluetooth
2.4 GHz
WiFi
2.4 - 2.5 GHz
Microwave
3 - 30 GHz

Fig 2.

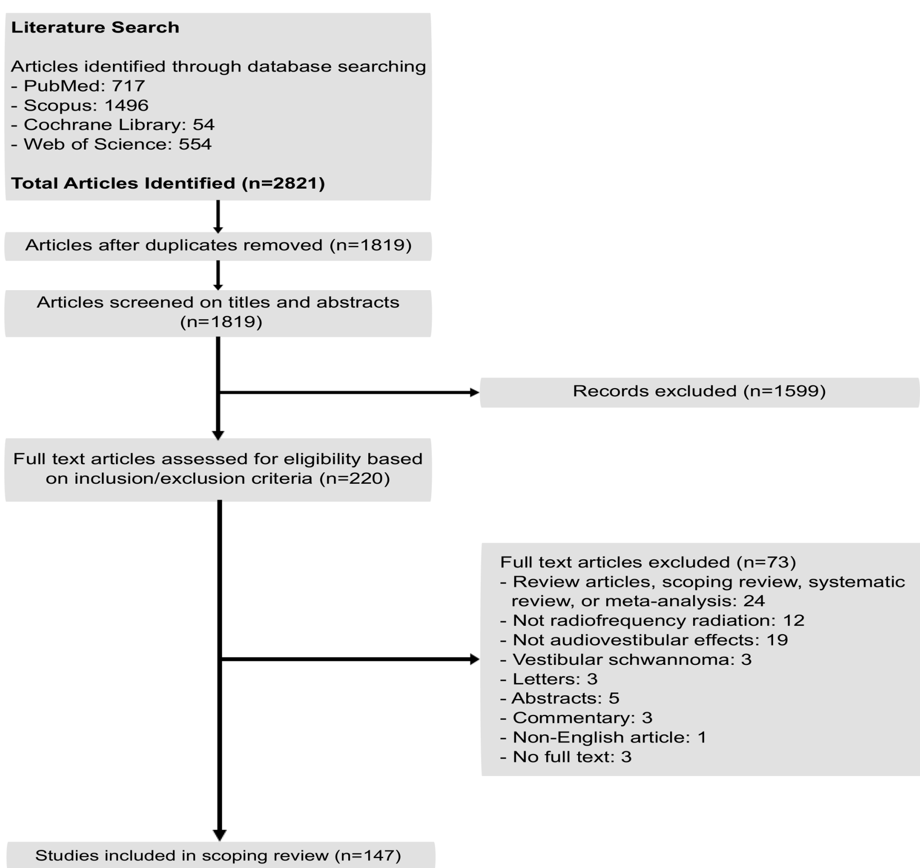
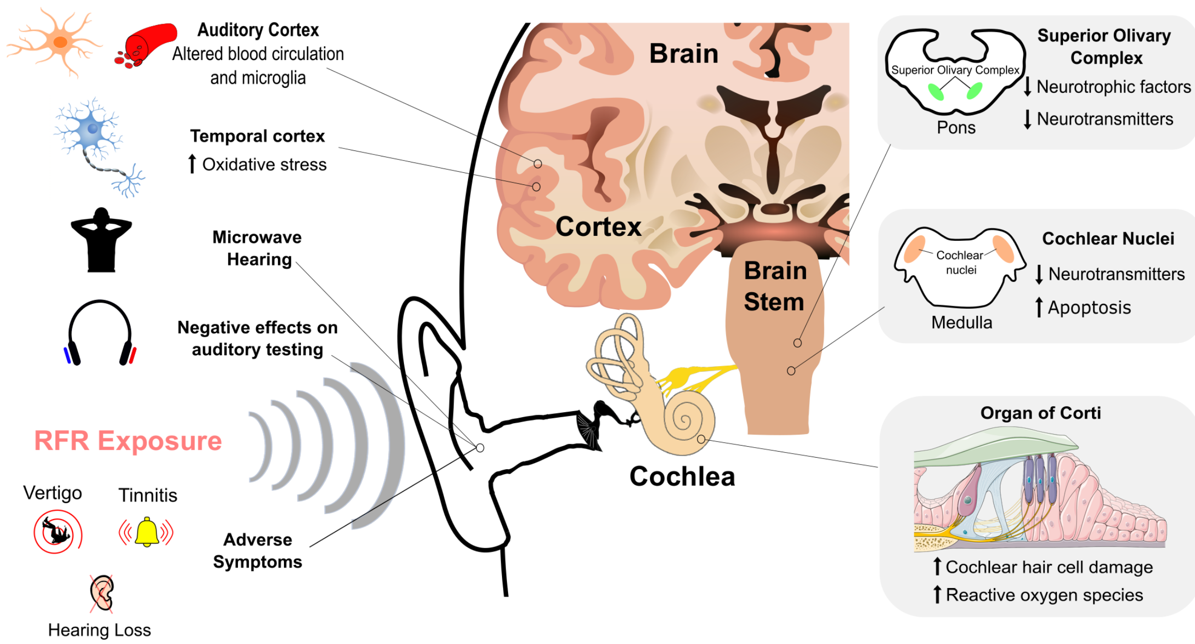
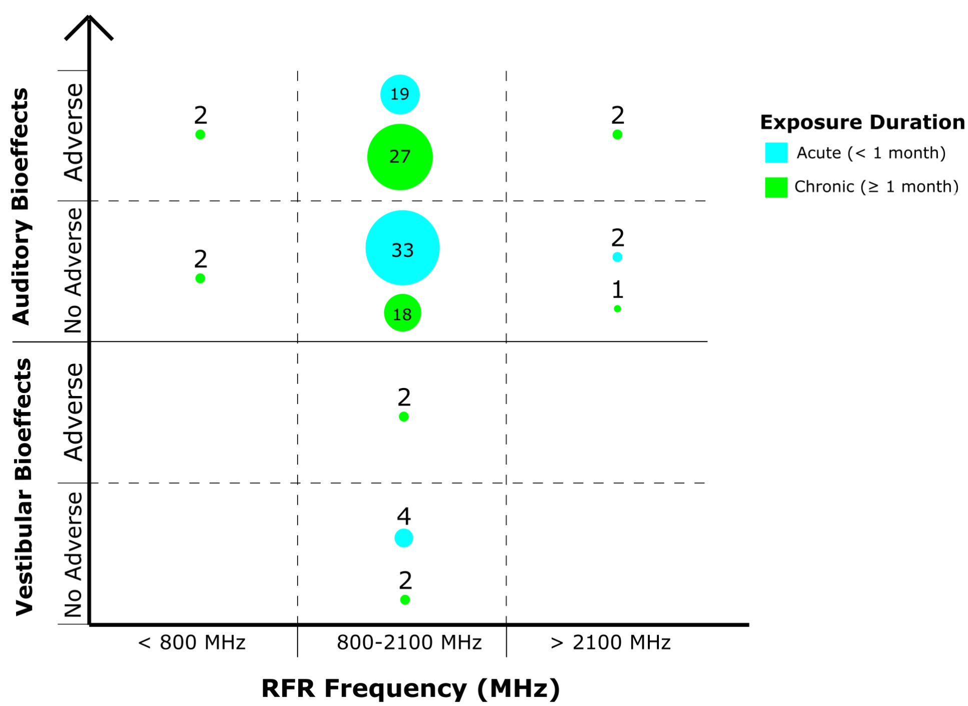

Literature Search
Articles identified through database searching
- PubMed: 717
- Scopus: 1496
- Cochrane Library: 54
- Web of Science: 554
Total Articles Identified (n=2821)
Articles after duplicates removed (n=1819)
Articles screened on titles and abstracts (n=1819)
Records excluded (n=1599)
Full text articles assessed for eligibility based on inclusion/exclusion criteria (n=220)
Full text articles excluded (n=73)
- Review articles, scoping review, systematic review, or meta-analysis: 24
- Not radiofrequency radiation: 12
- Not audiovestibular effects: 19
- Vestibular schwannoma: 3
- Letters: 3
- Abstracts: 5
- Commentary: 3
- Non-English article: 1
- No full text: 3
Studies included in scoping review (n=147)

Fig 3.



Auditory Cortex
Altered blood circulation and microglia
Temporal cortex
Oxidative stress
Microwave Hearing
Negative effects on auditory testing
RFR Exposure
Vertigo
Tinnitis
Hearing Loss
Adverse Symptoms
Brain
Cortex
Brain Stem
Cochlea
Superior Olivary Complex
Superior Olivary Complex
Pons
Neurotrophic factors
Neurotransmitters
Cochlear Nuclei
Cochlear nuclei
Medulla
Neurotransmitters
Apoptosis
Organ of Corti
Cochlear hair cell damage
Reactive oxygen species

Fig 4.



Auditory Bioeffects
Vestibular Bioeffects
Adverse
No Adverse
Adverse
No Adverse
2
19
27
2
2
33
18
2
1
2
4
2
< 800 MHz
800-2100 MHz
> 2100 MHz
RFR Frequency (MHz)
Exposure Duration
Acute (< 1 month)
Chronic (≥ 1 month)