Wireless technologies, non-ionizing electromagnetic fields and children: Identifying and reducing health risks

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Children today are conceived and live in a sea of wireless radiation that did not exist when their parents were born. The launch of the digital age continues to transform the capacity to respond to emergencies and extend global communications. At the same time that this increasingly ubiquitous technology continues to alter the nature of commerce, medicine, transport and modern life overall, its varied and changing forms have not been evaluated for their biological or environmental impacts. Standards for evaluating radiation from numerous wireless devices were first set in 1996 to avoid heating tissue and remain unchanged since then in the U.S. and many other nations. A wide range of evidence indicates that there are numerous non-thermal effects from wireless radiation on reproduction, development, and chronic illness. Many widely used devices such as phones and tablets function as two-way microwave radios, sending and receiving various frequencies of information-carrying microwave radiation on multiple simultaneously operating antennas. Expert groups advising governments on this matter do not agree on the best approaches to be taken. The American Academy of Pediatrics recommends limited screen time for children under the age of two, but more than half of all toddlers regularly have contact with screens, often without parental engagement. Young children of parents who frequently use devices as a form of childcare can experience delays in speech acquisition and bonding, while older children report feelings of disappointment due to 'technoference'—parental distraction due to technology. Children who begin using devices early in life can become socially, psychologically and physically addicted to the technology and experience withdrawal upon cessation. We review relevant experimental, epidemiological and clinical evidence on biological and other impacts of currently used wireless technology, including advice to include key questions at pediatric wellness checkups from infancy to young adulthood. We conclude that consistent with advice in pediatric radiology, an approach that recommends that microwave radiation exposures be As Low As Reasonably Achievable (ALARA) seems sensible and prudent, and that an independently-funded training, research and monitoring program should be carried out on the long term physical and psychological impacts of rapidly changing technological milieu, including ways to mitigate impacts through modifications in hardware and software. Current knowledge of electrohypersensitivity indicates the importance of reducing wireless exposures especially in schools and health care settings.

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Abbreviations: EMF, Electro-magnetic field; EMR, Electromagnetic Radiation; FCC, Federal Communications Commission (U.S.A.); ICNIRP, International Commission on Non-Ionizing Radiation Protection; IEEE, Institute of Electrical and Electronics Engineers; MF, Magnetic field; GSM, Global System for Mobile Communications; RFR, Radiofrequency radiation; SAR, Specific Absorption Rate (a measurement of the rate at which energy is absorbed into particular tissues, when exposed to RFR); SAM, Specific Anthropomorphic Mannequin (a physical model used to estimate SAR, based on a 220 pound male with a 12 pound head); HPG, Hypothalamic-Pituitary-Gonadal axis; HSP, Heat Shock Proteins; ORSAA, Oceania Radio Frequency Scientific Advisory Association; DECT, Digital Enhanced Cordless Telecommunications; ICBE-EMF, International Commission on the Biological Effects of Electromagnetic Fields; ELF-EMF, Extremely Low Frequency Electromagnetic Fields (0 − 3 kHz); CDMA, Code Division Multiple Access; UMTS, Universal Mobile Telecommunications System; LTE, Long Term Evolution; ROS, Reactive Oxygen Species

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Introduction. Children's exposures to wireless radiation are increasing rapidly

We live in the age of technological wonder, where the ability to respond to emergencies, engage in routine commerce, and even conduct warfare has been radically altered by wireless communications. At the same time, we are also in an age of technological imperatives; that is, the fact that something *can* technically be done has been misconstrued as an argument that this *should be done,* i.e., in favor of implementing that technology. Parents understand that—just because you *can* go skateboarding without a helmet and other protective equipment does not mean that is a *good* idea. From wireless baby monitors to the iPad potty for toddlers learning to use the toilet, Wi-Fi Barbie, tablets and cell phones, today's infants, toddlers, young children, and adolescents are surrounded by wireless technologies. None has been tested for their impacts on children. Especially when used at early stages of life these devices can interfere with social development, learning, and socialization. They also can have lifelong and potentially irreversible adverse biological effects.

"Children are not little adults and are disproportionately impacted by all environmental exposures, including cell phone radiation." American Academy of Pediatrics to the Federal Communications Commission (2013)[1]

Cell phones, tablets, and laptops typically operate as two-way microwave radios sending and receiving radiofrequency radiation (RFR) to and from internal and external antennas. Unchanged since 1996, RFR exposure standards for the use and operation of cell phones and other wireless devices rest on a crude physical model using an empty plastic ball for the head into which homogenous fluid is poured; this uniform medium cannot reflect the different densities and electromagnetic properties of developing physiology, morphology and tissues at different ages, and the greater vulnerability of infants, toddlers, and children. Health based standards have never been developed to take into account the vastly different technologies, uses and users employing devices today.

Although cellular communication systems and wireless technologies have demonstrated numerous direct benefits to society, they can also pose risks to the health and safety of the billions who are exposed to unnecessary levels of RFR throughout the life span. As demonstrated in this review, given the substantial experimental, epidemiological and clinical evidence that current levels of wireless radiation can be harmful, especially to the young, we concur with those experts who counsel that policies should be governed by the concept of ALARA—as low as reasonably achievable—while research continues to evolve.

The guiding principle of radiation safety, ALARA means avoiding exposure to radiation that does not have a direct benefit to you, even if the dose is small.[2]

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For more than a decade the American Academy of Pediatrics[3] and the American Academy of Child and Adolescent Psychiatry[4] advised that children age two and under have no screen time, yet infant and toddler use of devices is skyrocketing. That advice has now been modified to allow parentally supervised video calls for ages 18 to 24 months. The Pew Research Foundation surveyed parents in 2020 and 2021 and found that 8 out of 10 parents of a child who was age 11 or younger (81%) said their child had ever used a tablet computer in 2021 up from 68% in 2020[5]; 71% said their child had used a smartphone in 2021 (See Fig. 1). More recent numbers are sure to be higher, as the pandemic has led to increased reliance on digital

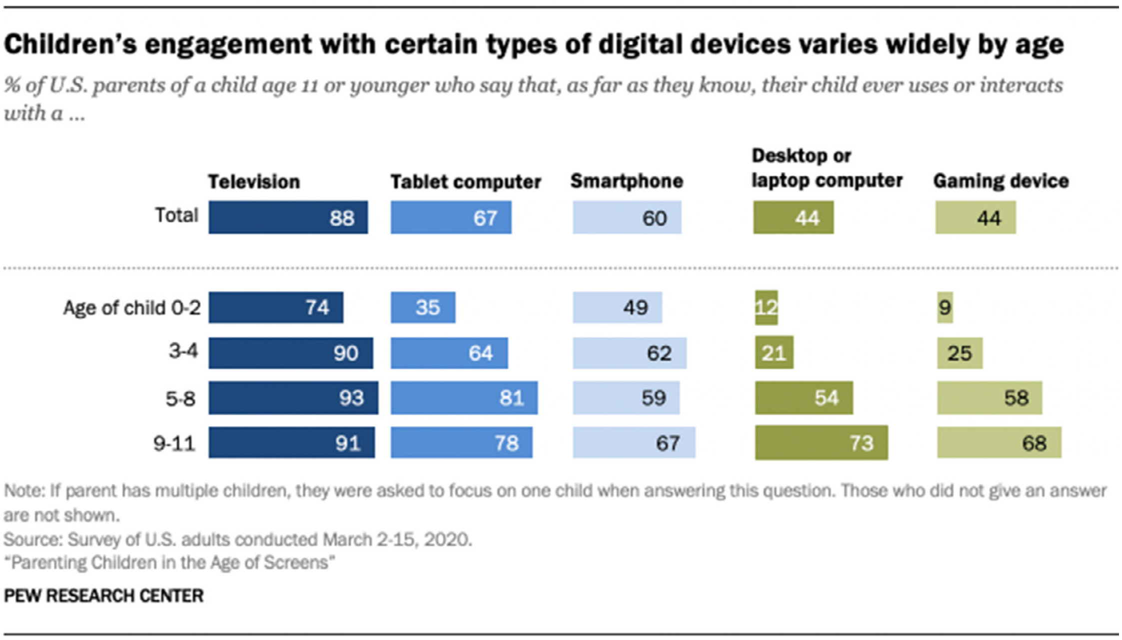

Fig. 1. Children's engagement with digital devices Survey 2020 by PEW Research Center. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

devices. Reports of serious behavioral problems including problems with self-control, socialization, language acquisition and the like have been associated with device addiction; and internet gaming disorder is on the rise in all age groups.[6]

Decades of research on RFR (including microwaves) indicate that everyday exposure to wireless devices can impact the physical, emotional and psychological health and well-being of adults and children.[7] A growing number of independent researchers find that while regulators, such as the U.S. Federal Communications Commission (FCC) and International Commission on Non-ionizing Radiation (ICNIRP) currently consider "low-level" exposures safe; these levels do in fact place children's endocrine, reproductive, and immune systems at risk. These current regulatory limits are based on the assumption that over-heating by high power RFR is the only established health effect to be avoided. Nevertheless, numerous studies find that nonthermal levels of RFR can cause major adverse effects such as induction of reactive oxygen species (ROS), DNA damage, cardiomyopathy, carcinogenicity, sperm damage, memory damage, and neurological effects.[8] As with many other chemical and physical hazards, there is evidence indicating that greater detrimental impacts take place when exposures occur during critical phases of growth and development, including pregnancy.[9]

Since the 1990s, member states of the European Union and the FCC have looked to the ICNIRP[10] and the Institute of Electrical and Electronics Engineers (IEEE)[11] for risk assessments and guidance on occupational and public exposure to RFR from all sources. These groups assume that only thermal effects (excessive heating) are to be avoided. In contrast, the International Commission on Biological Effects of Electromagnetic Fields (ICBE-EMF)[12] and the Oceania Radiofrequency Scientific Assessment Association (ORSAA),[13,14] among others, reject the assumptions on which ICNIRP relies, providing detailed grounds for their positions.[15] Moreover, the former editor-in-chief of the journal *Bioelectromagnetics*[16] contends that standards for evaluating wireless phones and other devices have not kept pace with developments in technology finding that nonthermal effects do occur and therefore current FCC standards do not protect public health.

Regulations on both sides of the Atlantic have in common that they are founded on risk assessments conducted in the 1980s and early 1990s by industry scientists and their affiliates in the IEEE. Despite a considerable weight of evidence indicating serious biological and environmental impacts of nonthermal levels of RFR, the FCC and the ICNIRP risk assessments of non-ionizing radiation from phones and other devices have remained unchanged for decades.

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When phones were first brought to market, children's cell phone use was unheard of. Today children are exposed to wireless radiation from cell phones as well as numerous sources in their homes, child care settings and schools as shown in Fig. 2. Several thousand apps have been developed for infants and toddlers to use on phones, watches and tablets with no research on their long-term physical or psychological impacts. (Fig. 2)

This article assembles key scientific information regarding why and how to reduce wireless exposures to the young, including limiting prenatal and neonatal exposures. The latest scientific and clinical studies on the biological impacts of wireless radiation and models of exposure are considered briefly in terms of unexplained trends in cancer, autism spectrum disorder, learning difficulties, attention deficit, behavioral and psychiatric disorders, and other increasing pediatric disorders. Finally, health professional and U.S. national policy developments aimed at protecting children from inappropriate and harmful exposures are presented, with specific recommendations and practices for safer use of technologies.

Electromagnetic radiation and biological effects

Radio communications lie at the heart of the cell phone and wireless radiation revolution via electromagnetic "radio waves" or RFR.

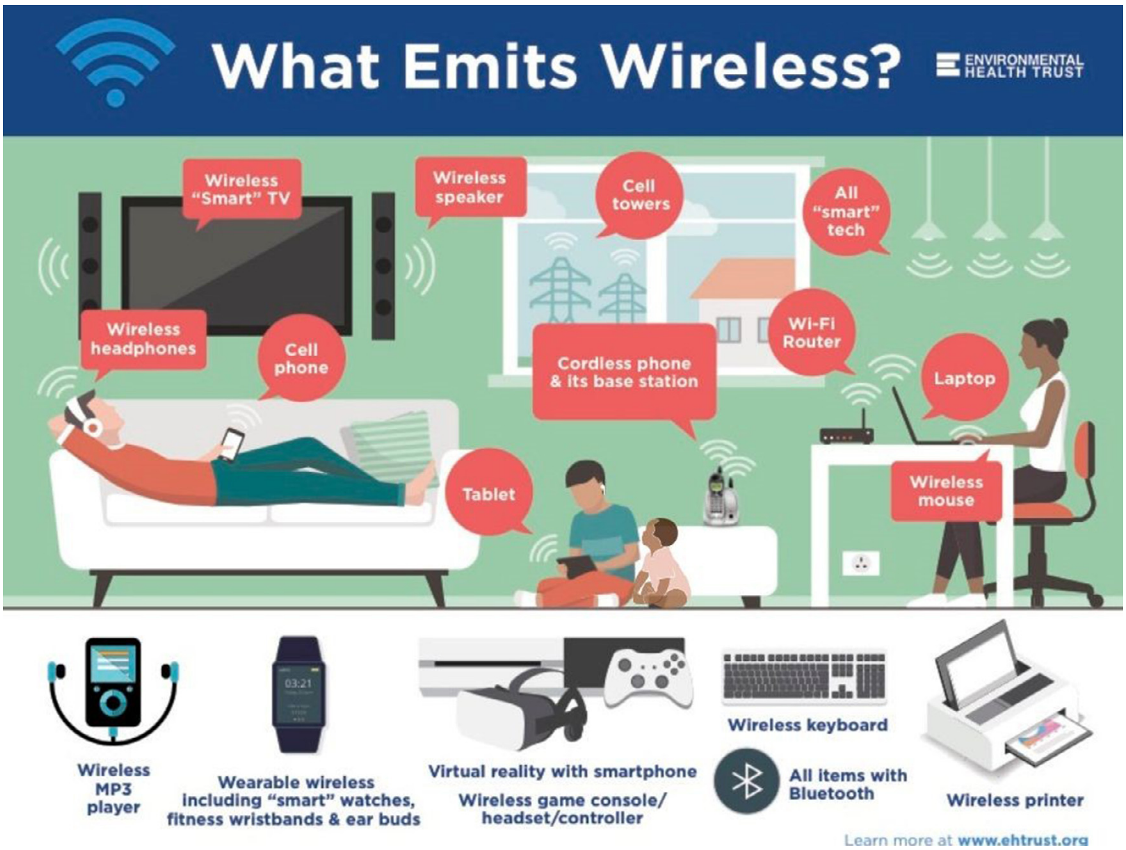

Fig. 2. Sources of wireless radiofrequency radiation in the home.

Electromagnetism

The theory of electromagnetism emerged in 1865 when James Clerk Maxwell unified Ampère's work on electricity, and Faraday's and others' work on magnetism into one unified theory.[17,18]

Simply put, an electric charge or the movement of electric charge (in electric currents through wires and devices) influences other charges or electrical currents at a distance. The influence, called a "field," results from attractive and repulsive forces between electrical charges. Positive and negative charges attract, while two charges of the same sign are forced apart. Of particular importance is how an oscillating charge creates a field that likewise oscillates, and this disturbance (called "radiation") propagates outward as a wave. Imagine a child flicking a skipping rope—the 'flick' propagates down the rope in the same fashion as the electric field propagates in the form of a wave. The theory was experimentally confirmed in 1887 by Heinrich Hertz.[19,20]

The duality of a wave is illustrated in Fig. 3. The oscillation can be described as a sine wave that depends both on the time and place of observation. The top frame of the Figure depicts the oscillation of the wave as seen by an observer standing in one place and looking over a period of time. One can imagine standing near the ocean and staring at a buoy as it undulates up and down as waves pass below. The bottom panel looks the same but depicts how at one instant in time the waves would look at every spot. Rather like standing on the same spot near the ocean and surveying open sea and all the waves before you. The characteristic features of the wave are its amplitude, A, its wavelength, λ (the distance between two sequential peaks) and its frequency, f (the number of oscillations per second, measured as Hertz [Hz] or reciprocal seconds [s^{-1}]). The relationship between these parameters, the cyclic frequency, ω, and the wavenumber, k, are illustrated in the Figure. Most importantly the multiplication of the frequency with the wavelength equals the speed of propagation, c.

Maxwell's theory predicted that the speed of light (visible light is a form of electromagnetic radiation) would be constant at 186,000 miles per second, confirming a measurement first made on earth (rather than by astronomical estimation as done by Ole Rømer and published in 1676[21]) by Hippolyte Fizeau in 1848.[22]

The frequencies of oscillation of electromagnetic waves can range from fractions of Hertz (a slow variation in field strength taking more than a second to complete) to billions of times a second. Each frequency can be exploited technologically in different ways and this is generally represented by the Electromagnetic Spectrum.

The electromagnetic spectrum

Physicians utilize electromagnetic radiation (EMR) in many forms. High-frequency, ionizing EMR is employed for diagnosis (e.g., X-ray and CAT scan imaging) and treatment (e.g., gamma-knife and other ionizing radiation treatments for cancer; non-ionizing ultraviolet radiation provides treatment of skin conditions such as psoriasis; infrared radiation is applied in physiotherapy and intensive care), while pulsed EMR are increasingly used in orthopedics and physical therapy. The electromagnetic spectrum includes visible light that forms a sliver of the spectrum (Fig. 4), with much of the remaining parts being invisible.

In public health, strong health and safety guidelines proscribe exposing infants and young children to the sun's rays beyond limited exposures. The problematic rays are found in the sun's ultraviolet (UV) light in the UVA and UVB frequency bands. While UVB is traditionally associated with direct DNA damage that leads to melanoma or less malignant forms of skin cancer, recent evidence indicates that UVA plays a greater role than previously assumed in the onset of skin cancers and can affect the immune system and other organs as well.[23] Other parts of the spectrum, especially that of blue light at 440 nanometers are used for their biological impacts on the skin to treat hyperbilirubinemia[24] by stimulating the production of di-hydroxy-vitamin D in the liver in jaundiced newborns. Untreated, the syndrome can result in bilirubin concentrations that can cause acute bilirubin encephalopathy and kernicterus− a permanent disabling neurologic condition. Blue light[25] is also known to interfere with sleep by impeding the production of melatonin, a natural hormone released by the pineal gland that is a potent anti-oxidant and free radical scavenger produced by sleeping in darkness.

Returning to the use of the spectrum for communication, the ability to transmit a travelling electrical field across space cannot itself establish a communication channel. For that to take place, information must be encoded into that transmission. The ability to code information on EMF was what Guglielmo Marconi

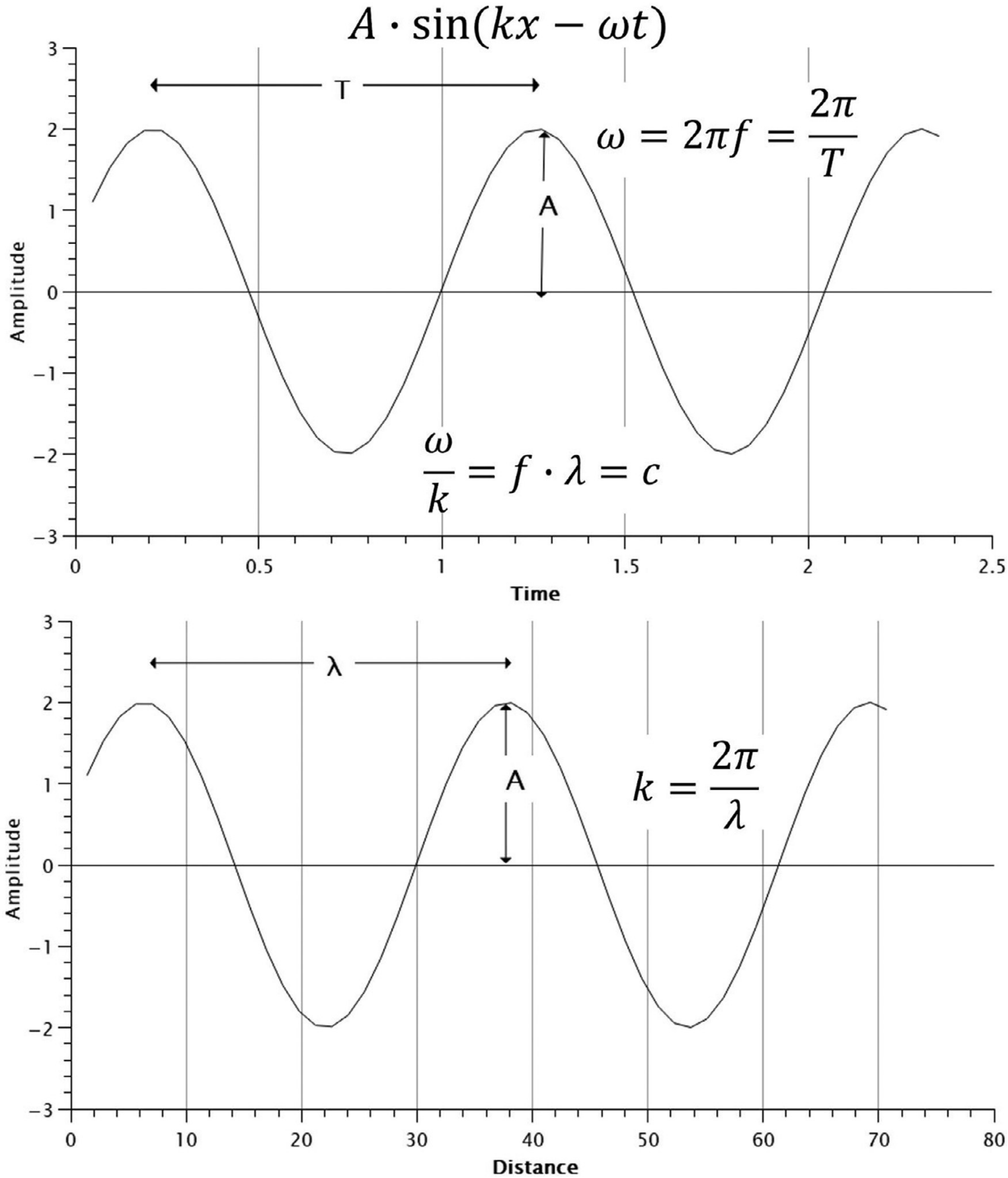

Fig. 3. Mathematical description of a continuous wave as a sine function. *A is the amplitude of the oscillation, f is the frequency, T is the time period for one complete oscillation, ω is the cyclic frequency (ω = 2pf) and k is the wave number.*

demonstrated in 1897[26] with his first transatlantic radio transmission.

Signals

The easiest way to encode information onto EMF is to turn the transmission on and off—Morse code in other words. Making a spark earned early Morse Code operators the moniker, "Sparky." Dots and dashes (a "digital" mode of communication) are comparable to the ones and zeros at the root of modern computing. More information can be transmitted by a careful modulation of the amplitude of the signal in proportion to the modulation of a sound, be it someone's

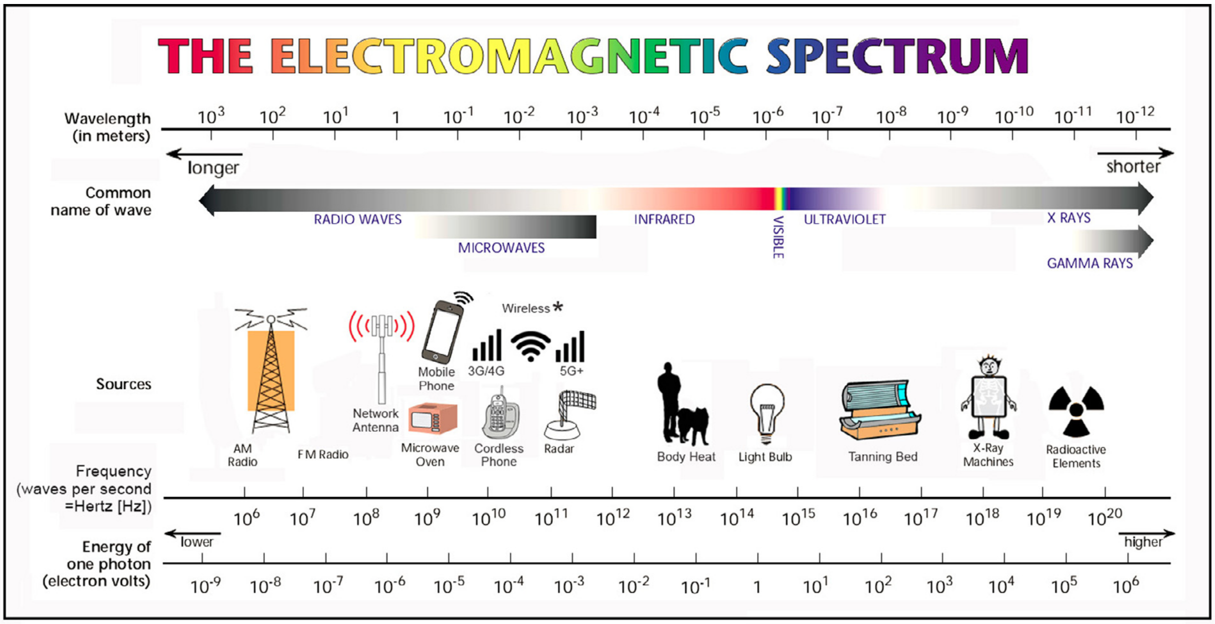

Fig. 4. Electromagnetic Spectrum
* Cellular and cordless phones; computers, laptops, tablets and peripheral equipment; antennae, Wi-Fi, access points and drones; monitors (e.g. security, medical, for babies); toys and entertainment systems; "smart" utility meters and appliances; control systems (e.g. indoor climate or lighting); "wearables"; power transfer/battery charging stations; and more. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

voice or music. This scheme, known as amplitude-modulated (AM) radio, dominated early radio and television broadcasts. However, there is a drawback with such a scheme in that only one operator can use the same radio frequency at a time. For two-way AM communication either, each side must wait for the other to stop and 'release' the frequency (hence the use of 'over' by radio operators) or there must be different carrier frequencies for each channel.

The first generation of cellular phones were little more than AM radio handsets working with 2 channel communication (by using a protocol known as Frequency Division Multiple Access[27] (FDMA) and transmitting to an antenna connected to the telephone network, often using relatively high powers of EMF, up to 5 Watts. Their transmissions could be famously picked up by ham radio operators, as the future King of England discovered to his chagrin, when an intimate conversation between then Prince Charles and his paramour, Mrs. Camilla Parker-Bowles was recorded by a scanner enthusiast.[28] Continuous analogue signals dominated telephone signals via copper wires that knitted together cities and countries, radio and television broadcasts right up until the early 1990s.

To overcome problems of limited exchange, and avoid interference and the embarrassment of royals, digital forms of transmission were introduced. The simplest form of digitization is to modulate a carrier signal, transmitting at a set frequency by multiplying it by zero or one. This is illustrated in Fig. 5.

The first panel in the Figure shows the base sinusoidal signal and is known as the "carrier frequency". The second panel is a digitization that turns on or off the signal. The bottom panel is the result of multiplying the two together, resulting in bursts - pulses- of transmission. A receiver tuned to the carrier frequency will translate the red envelope into ones and zeros, resulting in a digital series and information.

The increase in exposure to electromagnetic radiation

The quantity of data transmitted wirelessly and its associated radiation have increased many orders of magnitude since the inception of TV and radio programming. Rather than weekly anticipation of seeing a star on the Ed Sullivan Show or the next stage of a sitcom, we can now enjoy instant gratification with binge-watching, and endless offerings on many platforms, with important environmental implications,[29] including significantly increased energy and greenhouse gas emissions.

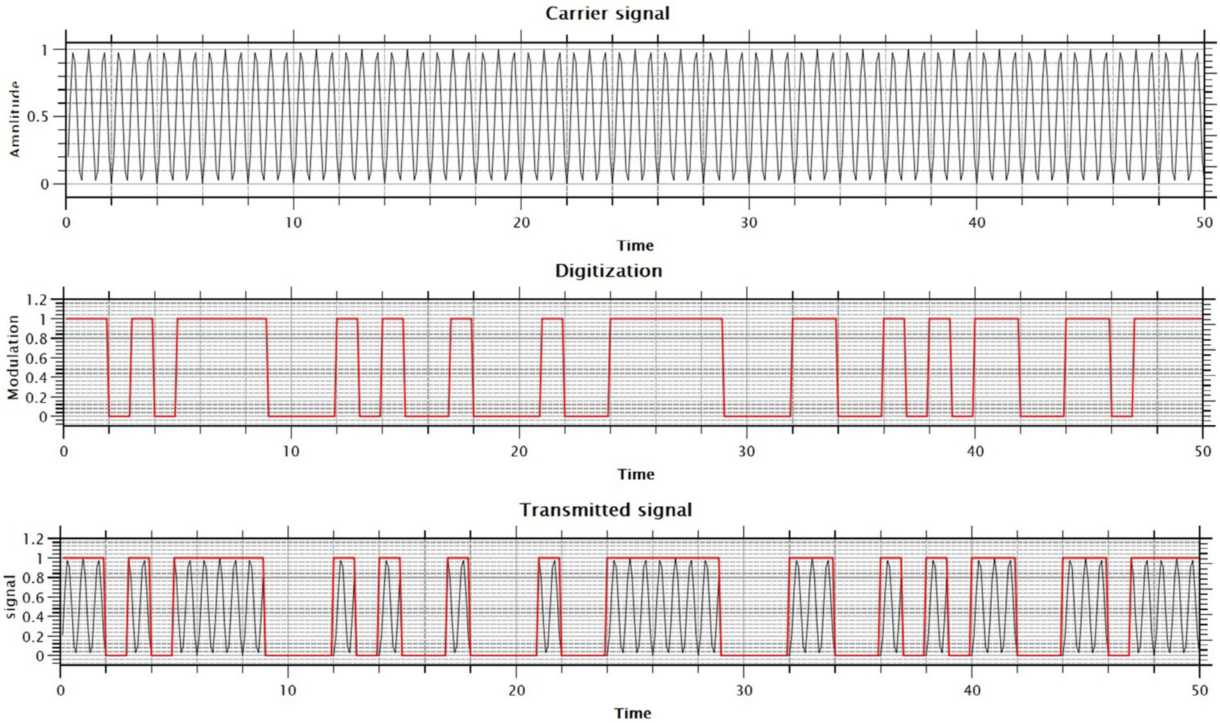

Fig. 5. A simple illustration of how a continuous carrier wave can be transformed into a pulsed signal for digital transmission. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since the inception of the mobile telephone age (the first commercial cellphone hit the marketplace in 1983[30]) 40 years ago there have been 5 generations of technological advances (see Table 1) culminating in the last 5th Generation (5G) Mobile networks. Each generation has led to consequent increases in exposure to EMR.[31] One often trumpeted claim is that the latest 5G networks will in fact be greener and reduce exposure levels. However, in discussing the energy implications of 5G rollouts, López-Pérez et al. noted in a recent survey that a 5G network may consume over 140% more energy than an equivalent 4G network.[32] Additionally, there is no corroborated evidence that 5G networks will reduce exposures. There are number of studies indicating the opposite will be true[33–36] Some industry experts report that ambient environmental exposures from near antenna installations from 5G and the densification of new wireless infrastructure can exceed those of current 3 and 4G networks up to 46 times.[33,37] 5G networks have multiple beam-forming antennas, located about every 100 m.[32] The public health and environmental impacts of 5G remain untested.

Some industry experts report that ambient environmental exposures near antenna installations from 5G and the densification of new wireless infrastructure can exceed those of current 3 and 4G networks up to 46 times.

Part of the reason for this increase in exposure with 5G is due to the fact that as higher frequencies are used atmospheric absorption and scattering increases. Because 5G frequencies operate along the millimeter wavelengths and signals cannot travel as far as previous systems, they are more prone to disruption from objects that interfere, such as walls and other barriers. Therefore, to maintain the same signal strength more base stations are required, a process known as "densification." Some estimates put the number of additional 5G base stations required for coverage in an urban environment to a 100-fold increase compared to an equivalent 4G network.[34] More base stations translate to more radiation. Another reason that greater exposures can occur is a

TABLE 1. Common cellular technologies and their respective frequency bands in the MHz (10^6 Hz) and GHz (10^9 Hz) ranges.[30]

Cellular technology	MHz frequencies	GHz frequencies
GMS (2G)	380 – 900	1.8 – 1.9
CDMA (2G & 3G)	400 – 900	1.8 – 2.5
UMTS (3G)	699 – 900	1.7 – 2.69
LTE (4G)	400 – 900	1.9 – 5.925
5G NR (5G) FR1	600 – 960	1.5 – 6.7
Bluetooth		2.4
Wi-Fi		2.45, 5 and 6
5G NR (5G) FR2	———–	24.25 – 71.0

The acronyms stand for Global System for Mobile communications (GSM), Code Division Multiple Access (CDMA), Universal Mobile Telecommunications System (UMTS), Long Term Evolution (LTE) and 5th Generation New Radio Frequency Range (5G NR FR). **Currently 5G NR FR1 is being nationally deployed, with limited applications of 5G NR FR2 being deployed in some major cities.**

result of the fact that the 5G standard relies on a new technological advance termed Multiple Input Multiple Output (MIMO) antennas. The number of users that can connect to a single base station increases by sharing out the frequency band to many more frequency channels (hence the requirement for higher frequencies) and by dividing the time each individual channel utilizes the same frequency band. In contrast to 2G to 4G standards, this division of frequency bands in 5G is multiplied by using beam-forming antennas. By using many small antennas and by closely timing individual transmissions on the same frequency, it is possible to form the signal into a tightly confined spatial beam from the base station directly to the user's 5G phone, 5G tablet or 5G computer. As long as 2 users are not standing together, they can both use the same signal frequency and not interfere with each other's transmission. These are known as "phased array antennas" and will form the heart of multiple beam-forming antenna and the need for MIMO in the 5G standard.[33] The electromagnetic frequencies utilized for wireless and cellular communications, from 1G up to 5G occupy the Megahertz (MHz) and Gigahertz (GHz) frequency ranges as depicted in Table 1.

How is EMF exposure quantified?

The metric used for measuring personal exposure from cell phones is called SAR (Specific Absorption Rate). It is a gauge of the rate of absorption of electromagnetic energy by the flesh of the user. Properly defined it is the rate of absorption of energy from a cell phone or other wireless device, measured in Watts per Kilogram (W/kg) averaged over a time period of 6 or 30 minutes distributed into a 1 g or 10 g volume within the plastic phantom 12-pound head of a large adult male filled with homogenous fluid or his 220-pound plastic body phantom. A local SAR of 1.6 W/kg is allowed for head and torso, and 4.0 W/kg is permitted for extremities which include the ear (the pinna).

Using a computer-controlled probe that dips into the fluid-filled phantom head (see Fig. 6), the electromagnetic field strength is measured at various points inside the model of 12-pound head of a large adult male. The SAR is then calculated by the equation,

$$SAR = \frac{\sigma |E|^2}{\rho} \tag{1}$$

where σ is conductivity of the saline solution at the frequency of interest, E is the electric field strength and ρ is the density of the media. The protocol of measurement is dictated by the IEEE standard C95.1-2019.[38] The human phantom is known as the Specific Anthropomorphic Mannequin (SAM) and is standardized by the IEEE.[39] The SAR rating has been criticized as under-estimating absorption for smaller persons and for children by a number of authors[40] because the dimensions of the SAM are based on a model of the 90th percentile of 1989 United States military recruits.[41,42,38] The homogenized saline liquid used to electrically mimic flesh cannot account for the varied and widely differing conductivities and densities of different tissues of different ages.[43] Underlying this model for estimating exposure is the assumption that the only harm that can be caused by an electromagnetic wave is heating of brain or body. In summary, if exposure heating results in a rise in core body temperature of less than 1 °C, then it is considered not hazardous. Criticisms of the SAR are further discussed in Section 7 on the need to update regulatory limits.

A further metric is the Ambient Power Density (PD), measured in Watts per square meter or milliwatts per square centimeter. The ambient PD metric measures the flow of electromagnetic energy per square meter from a distant source, such as a cellphone base station. In the US the safety limit for general public exposure to sources such as base stations, is set at 10 W/m^2 (sometimes quoted equivalently as mW/cm^2).

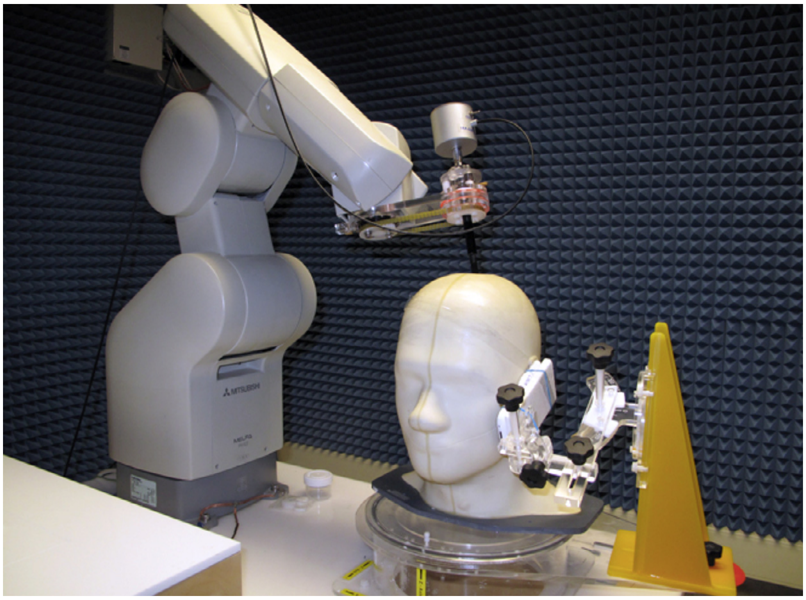

Fig. 6. Cell phone SAR RF test system using Specific Anthropomorphic Mannequin Model.

The origins of the ambient PD and the SAR regulations can be traced to the late 1950s when the U.S. Army and Navy became worried over potential harm to radar operators[44,45] from heating by carrying out studies on a handful of dogs, monkeys and rats. They had noted eye damage and burns from over exposure and the standard for PD was set at 10 W/m.[2,44,46] This became the established paradigm with the issuance of the first American standard in 1966 by the American Standard Association and then by the Institute of Electrical and Electronics Engineers (IEEE) for exposure to RFR and has remained ever since. Further research, including animal behavioral studies when exposed to EMF to a level that did not cause internal heating (of more than 1 °C) were used to confirm this initial assumption.[42] In 1996 the US Federal Communications Commission (FCC) set current guidelines for the allowable RFR exposure of the general public to RFR ranging from 300 kHz to 100 GHz (3G up to 5G and above).[47] based on a 1986 Report of the National Council on Radiation Protection & Measurements (NCRP) as well as the Institute of Electrical and Electronics Engineers (IEEE) C95.1-1991 standard.

Internationally, many national governments either take their cue for exposure levels from the FCC or from the International Commission for Non-Ionizing Radiation Protection (ICNIRP).[10]

A comparison of the allowed PD limits amongst counties is given in Fig. 7.

ICNIRP grew out of a working committee of the International Commission for Radiation Protection, a non-governmental organization representing professionals and bodies involved in radiation industries.[48]

Numerous publications have criticized ICNIRP as a close-knit invitation-only group that downplays and misrepresents research[49] indicating biological effects at nonthermal levels and

In 2021, the U.S. Court of Appeals for the District of Columbia Circuit issued its judgment in* Environmental Health Trust et al v. FCC*, finding that the agency had failed to provide a rational record of review of all submitted science and specifically had not shown evidence of examination of studies provided to the agency on the greater vulnerability of children, the impacts of long term exposures, environmental impacts or the failure to update radiation test procedures for cell phones and other wireless devices which have not changed in more than 27 years.

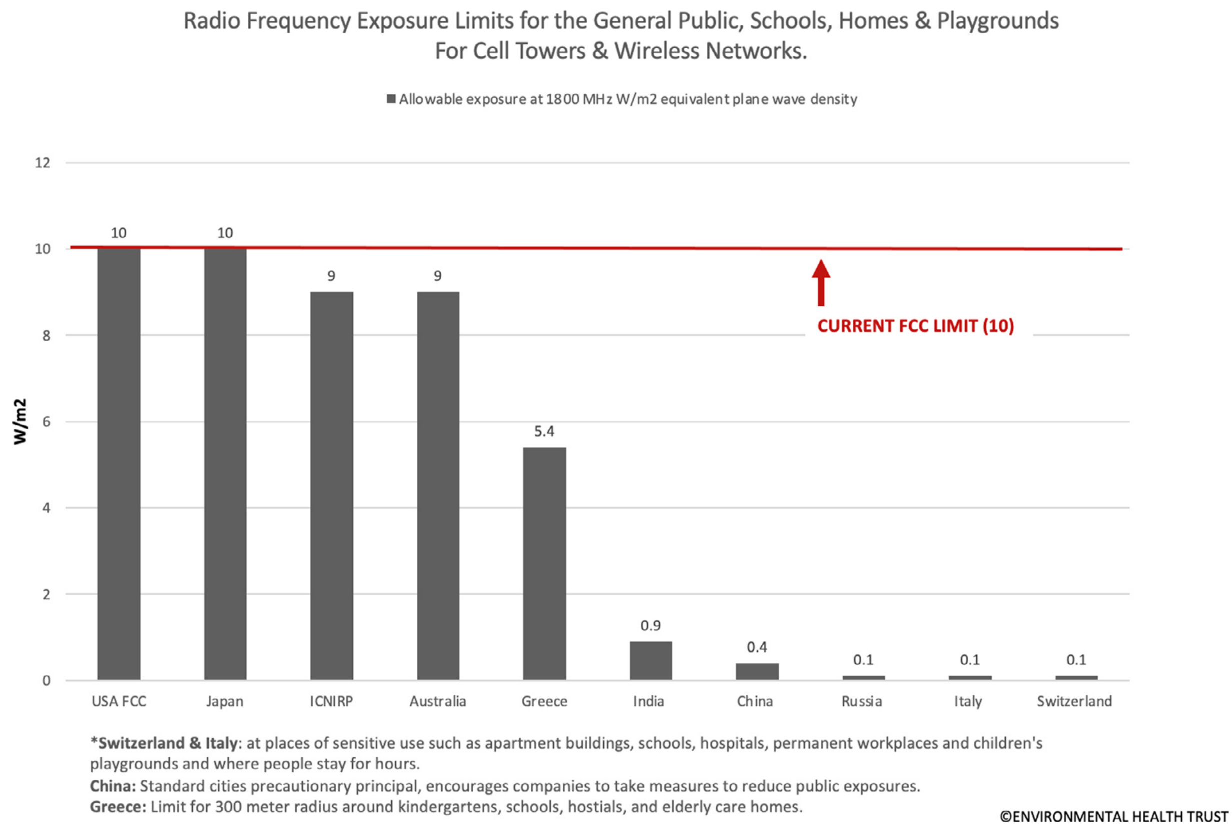

Fig. 7. Country variations for radiofrequency radiation exposure limits.

TABLE 2. ICNIRP and FCC SAR Limits in the U.S. and other countries

SAR Limits for Cell Phones and Wireless Devices	Whole -body average SAR (W/kg)	Head and Trunk * Localized SAR (W/kg)	Limbs and Extremities** Localized SAR (W/kg)	Examples of countries that adapted limits for cell phone and wireless device premarket tests
ICNIRP 100 kHz to 6 GHz All SAR limits averaged over 6 minutes. Local SAR averaged over 10 g of tissue.		Occupational		Europe, Mexico, China, Greenland, Canada (for over 6 GHz), most countries in South America except Bolivia, most countries in Africa
	0.4 W/kg	10 W/kg averaged over 10 grams tissue	20 W/kg averaged over 10 grams tissue	
		General Public		
	0.08 W/kg	2 W/kg averaged over 10 grams tissue cube	4 W/kg averaged over 10 grams tissue cube	
ICNIRP (2020) >6-300 GHz *6 minute averaging *ICNIRP states, "Local Sab is to be averaged over a square 4-cm^2 surface area of the body. Above 30 GHz, an additional constraint is imposed, such that exposure averaged over a square 1-cm^2 surface area of the body is restricted to two times that of the 4-cm2 restriction."*		Occupational		Australia
	0.4 W/kg	Local S_{ab} 100 mW/cm^2		
		General public		
	0.08 W/kg	Local S_{ab} 20 mW/cm^2		
FCC Occupational, averaging time is 6 minutes. General public averaging time ranges from 6 minutes to 30 minutes.		Occupational		United States, India, Panama, Korea, Vietnam, Canada (for under 6 GHz), Iran, Republic of Bolivia, Cuba
	0.4 W/kg	8 W/kg averaged over 1 gram of tissue cube	20 W/kg averaged over 10 grams tissue cube	
		General Public		
	0.08 W/kg	1.6 W/kg averaged over 1 gram tissue cube	4 W/kg averaged over 10 grams tissue cube	

ICNIRP's Head and Trunk tissues have both Type 1 and Type 2. ICNIRP defines Type 1 as all tissues in the upper arm, forearm, hand, thigh, leg, foot, pinna (visible portion of the outer ear) and the cornea, anterior chamber and iris of the eye, epidermal, dermal, fat, muscle, and bone tissue. ICNIRP defines Type 2 tissues: all tissues in the head, eye, abdomen, back, thorax, and pelvis, excluding those defined as Type-1 tissue. *Limbs do not contain any Type-2 tissue.

****FCC defines extremities as hands, wrists, feet, ankles, pinna/ ear.**

instead self-references its own commissioners, many of whom have a history of conflicts of interest.[50,51] ICNIRP and FCC limits for SAR are summarized in Table 2.

Despite innumerable studies demonstrating nonthermal biological effects of RFR, discussed below, ICNIRP and IEEE do not recognize non-thermal impacts as sufficiently "established" to be relevant to exposure limits.[7,8,31] Numerous scientific expert groups[7,29,52] such as ICBE-EMF and ORSAA emphatically do not agree with this view. Yet, the FCC reaffirmed their guidelines in 2019, by the expedient of simply reconfirming the existing 1996 standard.[53,54]

In 1996 the US Federal Communications Commission (FCC) set current guidelines for the allowable RFR exposure of the general public to RFR ranging from 300 kHz to 100 GHz (3G up to 5G and above).[47] This led to legal action against the FCC because more than 11,000 pages of published scientific studies and expert recommendations had been submitted to the FCC regarding the need to strengthen its RF exposure guidelines.[55] The FCC failed to provide a rational record of review of submitted science, and specifically did not take into account evidence on the greater vulnerability of children or environmental impacts. Human exposure limits and radiation test procedures for cell phones and other wireless devices have not changed in more than 27 years.

Public exposure limits for radiofrequency radiation from cellphone towers in Italy, Switzerland and Russia are 100 times lower than those of the U.S., last set in 1996.

Public exposure limits for radiofrequency radiation from cellphone towers in Italy, Switzerland and Russia are 100 times lower than those of the U.S., last set in 1996.

The World Health Organization (WHO) maintains a dedicated EMF project[56] which collates national government regulations[57] and offers advice to national government agencies. However, the WHO EMF Project has not performed health risk assessment of radiofrequency electromagnetic fields since 1993[58] and several have questioned its independence as well as its role in the global harmonization of EMF standards.[59,60] The World Health Organization International Agency for Research on Cancer (IARC) constitutes a separate entity from the WHO EMF project. IARC classified RFR as a class 2B possible carcinogen in 2011.[61] Within the past few years, the IARC advisory group has recommended a re-evaluation of the body of evidence on cell phone risks to human health, in light of mounting evidence of adverse impacts discussed here.

Since 1996, measurement of radiation permitted from any particular cell phone is made by testing temperature changes inside a plastic phantom 12-pound head of SAM (Specific Anthropomorphic Mannequin), filled with homogenous saline liquid to mimic the human brain with its diverse tissues and densities, making a 6 to 30 minute phone call, with a spacer between the head and the tested phone to allow for the ear/pinna.

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Physical mechanisms of the interaction of RFR and tissues

New 5G networks are using the frequencies of previous generations, but they can in addition employ higher submillimeter and millimeter wave frequencies. The higher the frequency, the less the radiation penetrates the body, but less penetration does not mean little or no biological impact. To the contrary, UVA and UVB are entirely absorbed in the skin, and can cause important immunological effects throughout the body including on the production of vitamin D. Indeed, immune effects of UV skin exposure can have consequences for the liver, kidney and other major organs, just as do the lower MHz and GHz frequencies that can penetrate deeper into the body. Importantly, man-made RFR used in wireless and medical devices can be modulated, polarized and pulsed, which greatly influences and can alter their ultimate impacts.[62,63] Electroceuticals constitute an expanding field of clinical applications involving a range of medical devices, from pain control in orthopedics to cancer treatment, biofeedback, and the use of low-strength pulsed electromagnetic fields.[64] As with pharmaceuticals, any agent that promotes healing may also promote illness. It is therefore pertinent to explore potential mechanisms of interaction between tissues and electromagnetic waves.

An important division in the spectrum happens at a frequency of approximately 10^{15} Hz (wavelength 10^{-8} m). While Maxwell's theory, as described above, considers light as classical waves, modern quantum theory embraces a dualism in considering light as both a particle and concurrently as a wave.[65] One can consider an oscillating packet of waves confined spatially and moving as one through space. This is known as a photon and the energy it contains is proportional to the frequency of its oscillation. As the frequency is reduced and wavelengths get macroscopically longer (the wavelength of visible light is measured in hundreds of nanometers, whereas of radio waves in the MHz range the wavelengths are measured in hundreds of meters) the quantum description of light is indistinguishable for the classical theory of Maxwell.

The energy inherent in a photon of light at frequencies of UV and above is enough to cause the ionization of biological molecules. That means that the absorption of the photon by the molecule can result in the breaking of chemical bonds, leading to the destruction of the molecule. Specifically for DNA such an occurrence can lead to the promotion of cancers. At frequencies of radio waves direct ionization of DNA or other molecules cannot happen.

Physical mechanisms of the interaction of RFR and tissues

At the submicroscopic level molecules can be regarded as collections of potentially charged atoms held together by chemical bonds as they share electrons. RFR also affects atoms that tend to be charged; either positively charged "cations" (sodium Na^+ or calcium $Ca^{2+}$for example) or negatively charged "anions" (chloride Cl^-). Consequently, bonds will react to an external electromagnetic field, even if its frequency is not high enough to lead to direct ionization. One can view such a perturbation as gently "nudging" ions. Under certain conditions bonds can change and form new chemicals. Indeed, microwaves are used commercially to speed up and alter products of chemical reactions using "microwave catalysis".[66] Dysfunctional chemical reactions can lie at the root of many distinct forms of ill health for living organisms.

Biological pathways for non-ionizing effects

There are several pathways[67–71] that may be involved in biological effects of RFR, including the induction of ROS leading to oxidative stress, activation of the ERK1/2 signaling pathway, and induction of heat shock proteins. One of the more accepted pathways to damage is the perturbation of Voltage Controlled Calcium Gates (VCCG) by pulsed EMF.[72] VCCGs are an integral part of cell membranes that are responsible for the transport of Calcium ions across the cellular membrane for signaling and regulation of the cellular homeostasis. In 2000 Panagopoulos et al. concluded that the ELF EMF components of wireless communication signals are a critical factor in understanding how exposures can lead to pathology.[72,73] Repeated irregular gating of electro-sensitive ion channels disrupts the cellular electrochemical balance and homeostasis leading to the overproduction of reactive oxygen species. The cascading effects of repeated exposures can lead to numerous biological endpoints including the weakening of cell membranes.

Disturbance in ROS homeostasis leads to a pathological state[74] termed "oxidative stress", which plays an essential roles in regulation of cancer progression. ROS are understood to regulate every step of tumorigenesis and have been found to be upregulated in tumors; this can lead to aberrant signaling. In addition to cancer, oxidative stress plays a role[75] in the development of many other chronic diseases, including diabetes and neurodegenerative syndromes. Reviews of animal and cell studies consistently find even very low non-ionizing EMF exposures are associated with increased oxidative stress. Children whose immune systems are still developing are more vulnerable to these ROS effects.[76,77] In 2019 Lai found strong indications that exposure to static and extremely low frequency electromagnetic fields also affects oxidative status in cell cultures and experimental animals.[67–72]

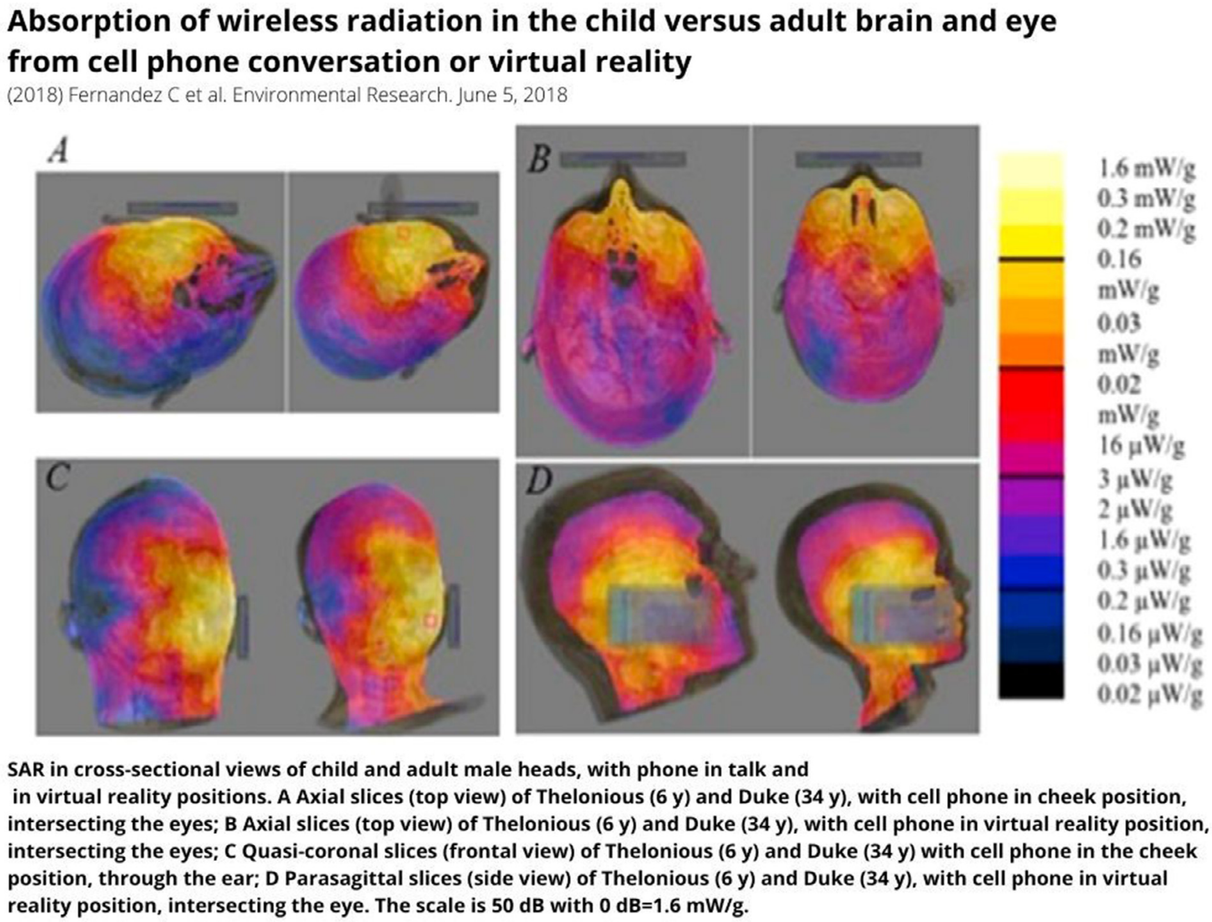

Fig. 8. Absorption of wireless radiation in child vs adult brain and eye from cell phone or Virtual Reality.[70] (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Children's unique vulnerability to wireless radiation

Children are more vulnerable to wireless radiation,[78–81] just as they are to other environmental pollutants[9] and medicines. Present and future generations will have many more hours of cumulative lifetime exposure to RFR, because exposures begin prenatally and continue throughout early and later life.

Children have a unique physiology, that results in proportionately greater RFR absorption compared with adults.[4] Children have smaller heads, resulting in shorter distances for RFR to travel to reach critical brain regions, and their brains contain more fluid that can absorb relatively more energy from radiofrequency radiation sources. Fig. 8[70] shows that simulations of exposure from cell phone use have determined that children absorb up to 10-fold greater RFR in the pediatric cerebellum, 10-fold greater in the bone marrow of the skull and up to 30-fold greater in the hippocampus.[82] Children's eyes can absorb 2 to almost 5-fold higher doses.

Children absorb proportionally more RFR than adults; about 2-fold greater in the pediatric cerebellum, ten-fold greater in the bone marrow of the skull and up to 30-fold greater in the hippocampus. Children's eyes can absorb 2- to almost 5-fold higher doses than adults.

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Children's brain and body tissues have a higher dielectric constant, a measurement of the ease with which electromagnetic fields can move through different media. Peyman[83] documented how the young brain has a higher dielectric constant due to the higher water content and less developed myelin sheath. Bony tissues also change over time depending on the degree of mineralization of the bone matrix. The largest age-dependent variation in dielectric properties is observed in bone because as an animal grows, the high water content of red marrow is transformed to the high fat content of yellow marrow.

Every tissue in the body has unique dielectric properties. For example, the distinctive dielectric properties of normal and cancerous breast are being employed to enhance detection of abnormal cells[84] and to devise EMR-based treatments for the disease.[85]

Pregnancy, infancy and childhood are periods of critical susceptibility, especially for the brain, which is developing rapidly.[86] Children have a faster rate of neuronal cell growth and the fatty protective sheath of myelin is not fully formed until the mid-20s.[87] Even very low levels of an environmental exposure early in development can have lifelong implications for neurodevelopment. Stem cells[88] are more active in children and have been found to be more sensitive to wireless frequencies than differentiated cells.[88]

Cell phones and wireless devices have premarket RF emission tests using the large adult SAM model, with an empty twelve pound head into which homogenous fluid is poured. Devices are not tested using a child's smaller head and body, nor with models of pregnancy.[42] Devices are also tested at a distance from the body, without direct contact between the antenna and the body or skull. This is why most smartphones, Wi-Fi devices and other wireless electronics have instructions, deeply buried in user manuals, which advise that devices be kept at a distance from the body.

Fig. 9[77] shows the radiation pattern simulated from a Wi-Fi tablet into the head of a 6 year old.

Reproduction and pregnancy

Reproductive capacity

Several, but not all reviews[89] of the effects of EMFs on male and female reproductive function have identified numerous serious effects that occur at levels of RFR that do not heat tissues. Gye and Park[90] and Jangid et al.[91] present a number of *in vivo* and *in vitro* experimental studies demonstrating that non-ionizing nonthermal EMF exposure can alter cellular homeostasis, endocrine function, reproductive function, and fetal development. Impacts on both male and female reproductive parameters have been reported, including: male germ cell death, the estrous cycle, reproductive endocrine hormones, reproductive organ weights, sperm motility, early embryonic development, and pregnancy success.

Mechanisms that appear to be involved at the cellular level include increases in free radicals and calcium ions [Ca^{2+}] related to effects of EMFs, which lead to cell growth inhibition, protein misfolding and DNA breaks.

Reproductive parameters reported to be affected by EMF include male germ cell damage and death. Females may experience impacts on the estrous cycle affecting ovarian follicles, reproductive endocrine hormones and reproductive organ weights. Effects on reproduction include impairments of early embryonic development, fertilization, miscarriage and a variety of pregnancy-related outcomes. As with other endpoints, experimental effects on reproductive function differ according to frequency, polarity, wave-form, strength (energy), and duration of exposure.

A robust body of research on the male reproductive system specifically has found decreased testosterone[92] as well as impacts to sperm viability,[93] motility and morphology[68,94–100] from current levels of RFR resulting from use of cell phones or other devices.

The induction of oxidative stress[101] is understood to be a key pathway of action that underlies the biological impacts of RFR on the reproductive organs and also can play a major role in the induction of cancer as discussed below.[101] At the cellular level, increased free radicals impact mitochondrial metabolism and affect nitric oxide levels and antioxidant mechanisms.[102] RFR may alter membrane transport and integrity, affecting ion (e.g., calcium) transport; these are among mediators of effects of EMFs that lead to cell growth inhibition, protein misfolding and DNA breaks. See Fig. 10.[56,92]

Acute exposure can stimulate plasma membrane NADH oxidase and increase the production of ROS. Increases in ROS can stimulate endothelial growth factor (EGF) receptors which in turn activate extracellular signal regulated kinase (ERK) pathways. The ERK pathway consists of subsequent activation of

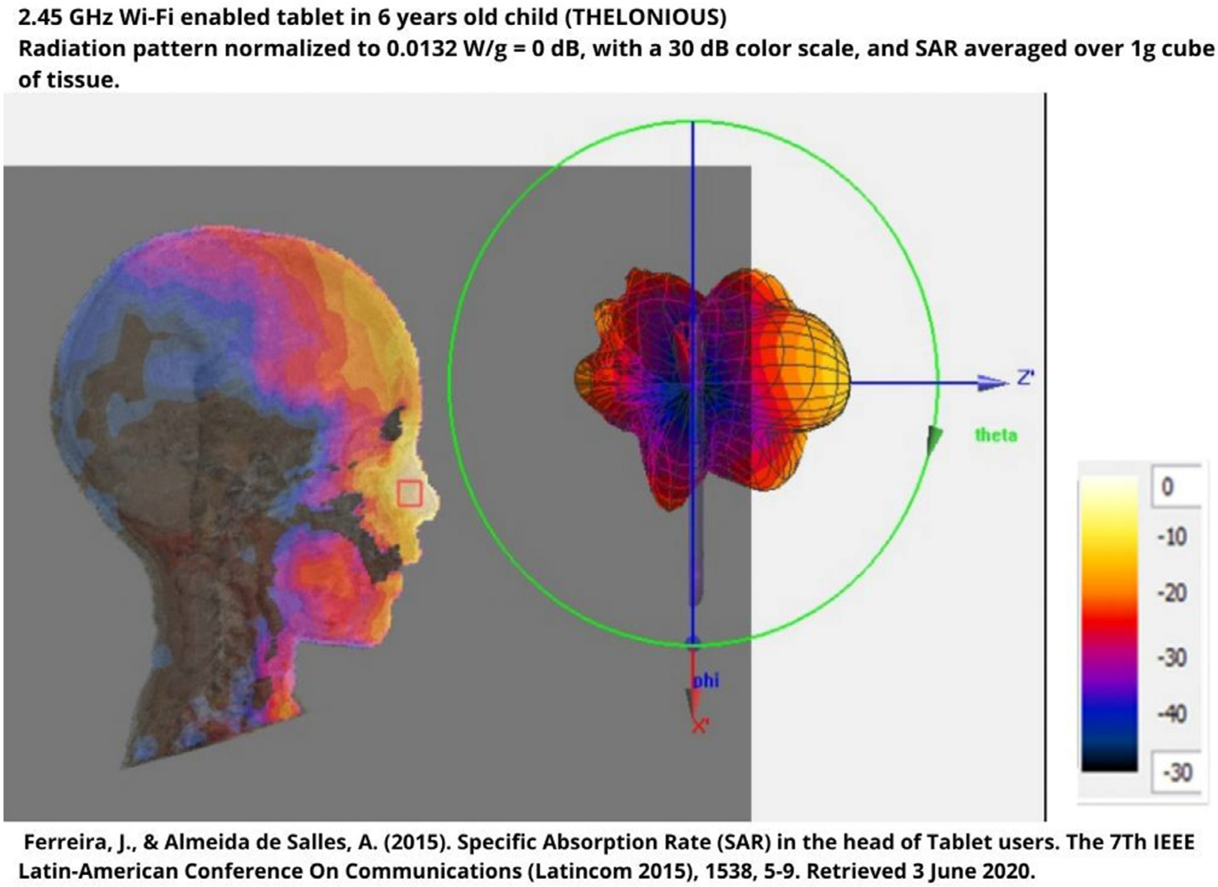

Fig. 9. Radiation pattern from 2.45 Wi-Fi enabled tablet into model of 6-year-old head. Radiation pattern normalized to 0.0132 W/g = 0 dB, with a 30 dB color scale, and SAR averaged over 1g cube of tissue.

Ras, Raf proteins, and mitogen-activated protein kinase (MAPK). The MAPK pathway also has a tumor promoting role. Chronic exposure to ROS can activate various stress kinases (p38 MAP kinase), stimulate the ERK pathway, and also lead to phosphorylation of heat shock proteins (Hsp) that inhibit apoptosis, thereby promoting survival of damaged cells and carcinogenesis. Hsp can increase the permeability of the blood-testis barrier and produce infertility. RFR also can interfere with membrane calcium channels and promote cancer by stimulating ornithine decarboxylase, a rate-limiting enzyme in polyamine synthesis.

Pregnancy is a critical window of vulnerability

In both animals and humans, prenatal EMF exposures have been linked with impaired development of structures and functions of the brain, as well as the reproductive organs and reproductive capacity of offspring. Experimental and epidemiological evidence indicates that prenatal impacts could range from impaired oogenesis and spermatogenesis, to reduced volume and number of brain pyramidal cells, other serious neuronal impairments, ovarian dysfunction[103] as well as increased DNA damage in multiple organs[104] of offspring.

Damage to oocytes in female offspring can in turn affect fertility as well as the health of following generations. Daily exposure of young Sprague-Dawley female rats for 2 h of GSM radiation for 1 and 2 months produced inflammation and impairment of ovarian function[103] consistent with endometritis, a growing problem for young adolescents. Intergenerational impacts are increasingly being understood; a 2021 study of more than 200 mother-daughter-granddaughter triads, found that granddaughters of those who had been in the top third of DDT exposure during pregnancy had 2.6 times the chances of having an unhealthy body mass index by their mid-twenties and

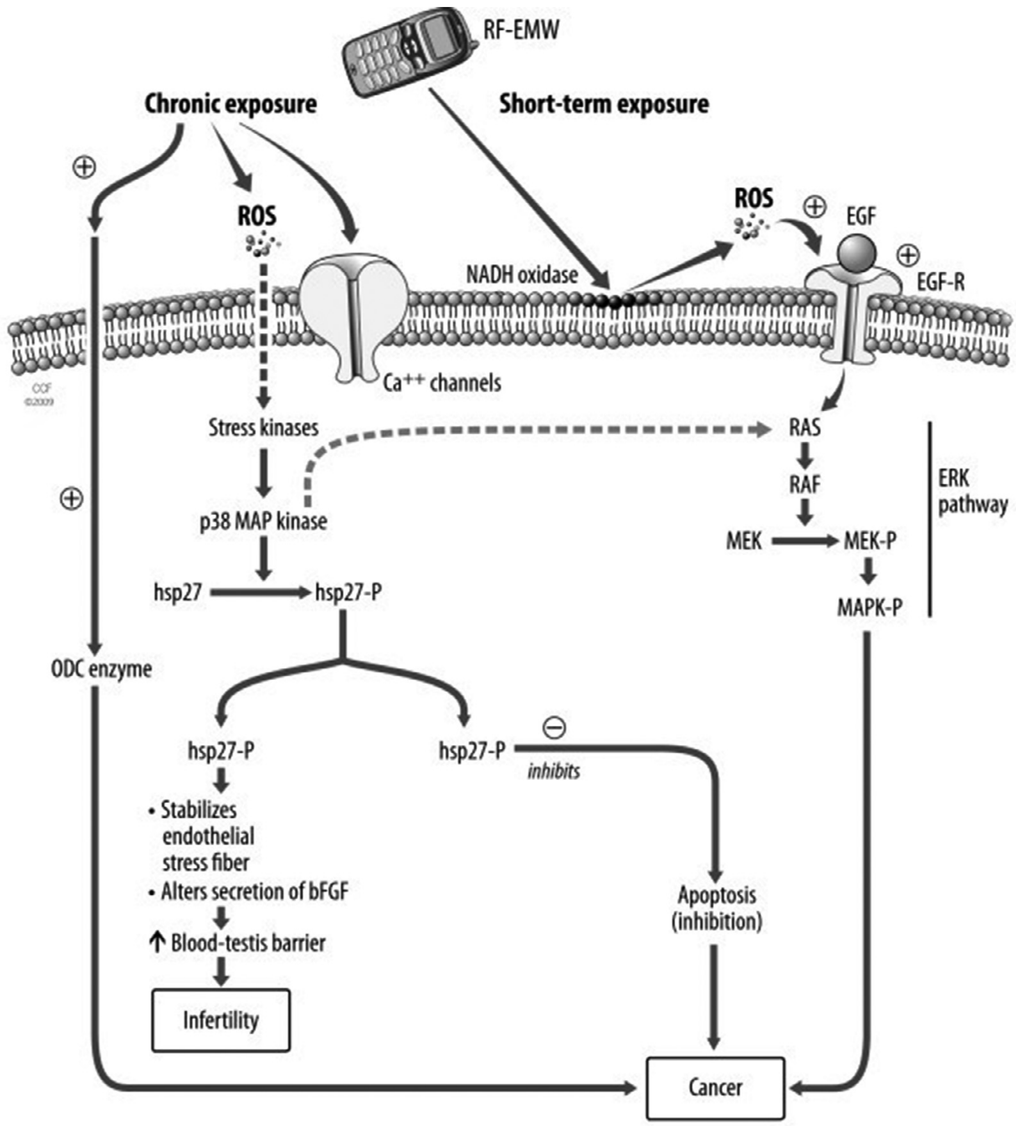

Fig. 10. Acute and chronic impacts of cell phone radiation on male reproduction. The Figure shows various acute and chronic cellular targets of radiofrequency electromagnetic waves (RF-EMW).[56,92]

were more than twice as likely to have started their periods before age 11—both of which increase their chances of developing breast cancer and other chronic illnesses later in life.[105]

Toxicological evidence of adverse impacts of RFR

Experimental studies form the foundation for evaluating pharmaceutical agents and other chemical and physical environmental exposures that can affect pediatric health. *In vitro* studies of well-established animal cell lines and human cell lines constitute one effective source of information that can be used to predict and prevent harm in humans. Employing validated rodent and other models, both short term and long-term *in vivo* studies on rodents and other animals are employed to clarify physiological consequences of exposures.

Studies of prenatal impacts can yield information on birthweight along with longer term consequences for health of offspring into adulthood. While the key male role ends at fertilization, damage to sperm *in utero* may have transgenerational effects on offspring.[106] There is growing evidence that male-mediated factors relating both to preconception and fertilization, as well as prefertilization and perifertilization exposures also play roles in determining health outcomes of progeny. In addition, early-life RFR exposures have been demonstrated to cause a range of negative impacts on male and female reproductive health, including damage to the testicular proteome[107] and low birthweight. After a month of 4 h daily controlled exposure to nonthermal levels of cell phone radiation, signaling proteins in the rat testes and sperm production were significantly altered, indicating impaired reproductive function and increased cancer risk.

Experimental studies are especially useful in understanding the roles of avoidable early-life environmental exposures on outcomes that affect children and adolescents, since controlled human studies are unethical. As a result, most human studies that can be used to clarify the impact of RFR are observational. Frequently, such studies are opportunistic, complex and expensive, and also challenging to interpret with poor quality longitudinal data, and limited exposure data, particularly with evolving uses of ever-changing technologies. In the real world, children are exposed to numerous sources of RFR at various frequencies and modulations throughout their daily lives. Smart phones can operate with 5 or more antennae simultaneously sending and receiving radiation to and from towers or routers, as most apps are set to update automatically. Yet, most experimental studies only look at a single frequency at a time.

Prenatal exposures and the central nervous system

Over the past two decades a number of experimental investigations have found that prenatal exposure to some EMF negatively affects both the structure and function of the adult central nervous system (CNS).[108–110] As an example, a series of experiments by Odaci, Bas and Kaplan and colleagues measuring impacts through stereological analysis demonstrated that rodents exposed prenatally to 900 MHz had fewer cells and more indications of damage in various brain regions of the hippocampus responsible for learning and memory.[111] Likewise, studies on postnatal exposures of 8 week old rats also found impacts on hippocampal pyramidal cells.[112,113] This team also found prenatal and postnatal impacts occurred to the Purkinje cells in the cerebellum. The cerebellum is critical to memory, balance and impulse control and appears especially vulnerable to RFR. Others have hypothesized that RFR might also alter the membrane current of Purkinje cells within the cerebellum. Haghani et al. evaluated properties of Purkinje cells[108] following prenatal exposure to 900 MHz EMF and found that exposed progeny had significantly reduced spontaneous cell firing. While these areas of the brain have been well characterized after prenatal EMF exposure, it is likely that many other areas of the brain are similarly affected.

Prenatal exposures in humans alter behavior and cognition in offspring

Although they are few in number, human studies investigating *in utero* exposure to wireless and other non-ionizing EMF have found a variety of adverse effects on pregnancy outcomes as well as the health of offspring regularly exposed to EMF or EMF/RF.

Several studies by a team from Kaiser Permanente lead by Dr. De Kun Li report a range of impacts to pregnancy and offspring. They measured pregnant women's exposure to magnetic fields (MF) early in pregnancy using an EMDEX Lite meter (Enertech Consultants Inc.) that measures magnetic field MF exposure for 24 h during a typical day, and providing a detailed diary of activities to allow the researchers to: (1) identify locations of daily activities (at home, at home in bed, in transit, at work, and other); (2) verify if activities were reflective of a typical day; and (3) examine if locations and activities were associated with high MF exposure. Women and their progeny were followed over several years. After controlling for multiple other factors, they found that women who were exposed to higher MF levels had 2.7 times the risk of miscarriage compared to those with lower MF exposure, a finding that corroborated earlier research by the same team.[114] Later publications also found higher *in utero* MF exposures associated with childhood obesity, asthma, and ADHD.[115–117] Similarly designed research[118] that measured MF exposure with the EMDEX meter found lower neural volume and bud length, measured by ultrasound, in embryos of women with higher workplace and other exposures to EMF, who were seeking induced abortion of unwanted pregnancies that were terminated in the first trimester. Women in the top quartile of MF exposure had a four-fold increased risk of a shorter embryonic bud length than those in the bottom quartile.

Greater habitual self-reported maternal mobile device use was associated with less infant recovery upon reunion.[119]

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Teens who used the phone against one side of their head scored more poorly on tests that measured memory skills specific to the most highly exposed brain regions.

Behavior and cognition in children and adolescents affected by cell phones

Researchers at the University of California School of Public Health in Los Angeles published studies in 2008 (13,159 children)[120] and 2012 (28,745 children)[121] that found that exposure to cell phones prenatally—and, to a lesser degree, postnatally—was associated with behavioral difficulties such as emotional and hyperactivity problems at the age of school entry. Although smaller studies have not found an association, in 2017 the largest study to date of 83,884 mother-child pairs in the five cohorts reported that high prenatal cell phone use was linked to hyperactivity/inattention problems in children, while no prenatal cell phone use was linked to low risk for any behavioral problems. The association was fairly consistent across and between these large cohorts. The nearly 40% of the cohort[122] reporting no cell phone use during pregnancy were much less likely to have a child with overall behavioral or emotional problems, while those with the highest reported use during pregnancy had 1.5 times more such problems documented in their children. The authors indicate that the "interpretation of these results is unclear as uncontrolled confounding may influence both maternal cell phone use and child behavioral problems." Greater habitual self-reported maternal mobile device use was associated with less infant recovery upon reunion.[119]

In addition, two studies reported consistent evidence associating RFR with lower figural memory performance in adolescents. Foerster et al.[123] confirmed Schoeni et al[124] in a larger study population of 843 adolescents. Teens who used the phone against one side of their head scored more poorly on tests that measured memory skills specific to the most highly exposed brain regions

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Behavior in animals

In addition to effects on brain development, pre- and post natal EMF exposures in numerous studies have found that cell phone radiation significantly affects a range of learning, memory, and behavior disorders in rodents.[125–136] Thus, Aldad et al. showed that prenatal exposures to conventional cell phone radiation throughout pregnancy resulted in impaired memory and hyperactive behavior, as well as altered neuronal developmental programming, glutamatergic-synaptic transmission onto pyramidal neurons of the prefrontal cortex. Fragoupoulou and Margaritis demonstrated in several studies that animals exposed to radiation have impaired performance on several standard measures of learning. Employing the standard Morris water maze test of hippocampal-dependent spatial memory, they showed that just 2 h per day of exposure to pulsed nonthermal cell phone signals of 900 MHz resulted in significant deficits in performance in exposed animals. Moreover, sham-exposed animals showed the expected preference for the target quadrant, while exposed animals showed no preference. These results indicated that the RFR exposed mice had deficits in their capacity to consolidate and/or retrieve and recall learned spatial information.

Despite these and numerous other studies demonstrating nonthermal impacts of RFR, standard setting groups such as IEEE and ICNIRP generally dismiss experiments that use actual transmitting devices (cell phones, Wi-Fi routers) in their studies, arguing that the exact exposures are not adequately quantified. Indeed, it is true that real devices emit constantly varying signals and erratic pulsation patterns that are more bioactive than can be produced through controlled laboratory simulations.[137] A number of other expert groups including the ICBE-EMF and ORSAA contend that employing actual phones and devices in controlled studies with shielded systems can yield important findings that are more realistic than those achieved through other means. In fact, experimental studies employing real mobile phone exposures are fairly consistent in showing adverse effects.[138] As an example, Aldad and colleagues[139] provided evidence that prenatal exposures to RFR from an operating phone significantly alter behavior of offspring.

Mice prenatally exposed to cell phone radiation from operating phones (800-1900 Mhz) through gestation exhibited behavioral and neurophysiological alterations that persisted into adulthood.

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The prenatally exposed mice were more hyperactive, with diminished memory and decreased anxiety. Findings further demonstrated impairment of glutamatergic synaptic transmission among pyramidal cells in the prefrontal cortex associated with these behavioral changes, suggesting a mechanism by which these exposures could lead to increased prevalence of neurobehavioral disorders. There was a significant trend across the groups treated for 0, 9, 15, and 24 h/day demonstrating that evidence of damage increased in direct proportion to the amount of exposure the animals experienced. Mice prenatally exposed to cell phone radiation from operating phones (800-1900 Mhz) through gestation exhibited behavioral and neurophysiological alterations that persisted into adulthood.

Mice exposed to mobile phone radiation at levels well below the permissible ICNIRP exposure limits for human-head exposure (SAR 2 W/kg) induced hippocampal lipidome and transcriptome changes that may underlie brain proteome changes and memory deficits.

In another example, Broom exposed mice to non-thermal levels of long-term evolution wireless (LTE) 1846 MHz downlink from late pregnancy (gestation day 13.5) to weaning (postnatal day 21) and observed 28-day-old offspring. They found significant effects on both eating behaviors and activity, and concluded that repeated exposure to low-level RFR in early life may have persistent and long-term effects on adult behavior.[140]

After finding cell phone radiation exposure affected spatial memory in mice, researchers from the Department of Cell Biology and Biophysics at the University of Athens, Greece conducted experiments investigating brain proteome responses in mice following whole body exposures to mobile phone or wireless DECT base radiation.[141] They found that long-term irradiation from both sources significantly altered the expression of 143 proteins in total, in critical brain regions such as the hippocampus, cerebellum, and frontal lobe. They speculated that these "underexpressed" or "overexpressed" proteins following EMF exposures may play a role in short term or long-term effects of RFR reported in humans as a consequence of mobile phone exposure, including memory deficits, headaches, sleep disorders, and brain tumors.

Mice exposed to mobile phone radiation at levels well below the permissible ICNIRP exposure limits for human-head exposure (SAR 2 W/kg) induced hippocampal lipidome and transcriptome changes that may underlie brain proteome changes and memory deficits.

Thus, Fragopoulou et al. showed that phone radiation (SAR 0.022−0.366 W/kg), well below ICNIRP limits for human-head exposure but comparable to SAR levels produced in human brain regions induces substantial phospholipid fatty acid remodeling in the brain, on the one hand, and on the other hand, alters the expression of genes that are implicated in lipid metabolism. These mechanisms are hypothesized to account for the deficits in memory that this group has reported.[142] Mice exposed to mobile phone radiation at levels well below the permissible ICNIRP exposure limits for human-head exposure induced hippocampal lipidome and transcriptome changes that may underlie brain proteome changes and memory deficits.

Carcinogenicity

In 2011 WHO/IARC designated wireless RFR as a Class 2B "possible" carcinogen based largely on studies of heavy cell phone users, that found increased risks for tumorsboth glioblastoma brain tumors and acoustic neuroma, as well as some experimental data with animals. Earlier, in 2002, magnetic field ELF-EMF was also classified Group 2B possible carcinogen due to studies associating residential magnetic field exposure with childhood leukemia.[143] This association continues to be observed.[144,145]

Since the 2011 WHO/IARC designation, several large animal[71,146–148] and case-control human[149–152] studies investigating carcinogenicity have been published associating RFR with cancer. A 2020 systematic review and meta-analysis[153] of case-control studies found that 1,000 or more hours of cell phone use, or about 17 min per day over 10 years, was associated with a statistically significant increase in tumor risk.

The NTP found significant increases in relatively rare and highly malignant schwannomas of the heart and gliomas in male rats. These tumor types are the same histotype found to be increased in epidemiological studies of long-term cell phone users.

Experimental carcinogenicity evidence

Every agent proven to cause cancer in humans will also produce it in animals when adequately tested—World Health Organization, International Agency for Research on Cancer

The international gold standard for rodent carcinogenicity studies has been developed by the U.S. National Toxicology Program (NTP), a program supported by several major federal agencies (NIH, CDC, FDA) that carries out transparent studies. To date the NTP has evaluated more than 600 different physical and chemical agents for their potential to cause cancer in animals under carefully controlled conditions. Every agent proven to cause cancer in humans will also produce it in animals when adequately tested—World Health Organization, International Agency for Research on Cancer.

Every agent proven to cause cancer in humans will also produce it in animals when adequately tested—World Health Organization, International Agency for Research on Cancer

In 2018, the NTP released the results of their large-scale rodent studies on cell phone radiation, which used non-thermal levels of RFR designed to mimic cell phone exposures. Especially relevant for pediatrics and long-term human impacts is the finding that the rodents exposed prenatally to RFR had significantly lower birth weights compared to unexposed animals. This finding constitutes an important signal that nonthermal radiation levels can impair development, as low birth weight is understood to reflect an important lifelong risk factor for adult health.

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The NTP study also reported increases in DNA damage[71] in both mice and rats and the induction of cardiomyopathy of the right ventricle in male and female rats.[147,148]

When it was completed in 2018, the NTP study, which followed long-established protocols, was the largest rodent bioassay ever conducted on cell phone radiation that began with prenatal exposures and ended after 24 months of exposures. Soon afterwards, the Ramazzini Institute[146] employing similarly controlled protocols released its findings from an even larger animal study of 2448 rats, which employed both similar and lower exposures comparable to those of base stations such as Wi-Fi, and observed the same types of malignant tumors—schwannomas of the heart—in male rats. Overall, these two large scale animal studies alongside the human data[153] provide reasonably strong evidence of the potential for non-thermal levels of RFR to cause cancer in humans.

Analysis of the NTP and Ramazzini data according to current risk assessment guidelines concluded that to be consistent with other toxicological assessments, the protection of children requires that U.S. government

FCC limits should be strengthened by 200 to 400 times.[154]

U.S. RFR exposure standards would lower current standards by 200 to 400 times, if they were consistent with usual methods for assessing risks for chemical and other hazards.

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Cancer epidemiology—Case-control studies

The multi-nation Interphone case-control study[155] from 2010, defined a cell phone user as someone who made one call a week for 6 months. That study did not include any cases from the U.S., was led by the IARC, and reported no overall increased risk of brain cancer with cell phone use, but did find that the highest users of phones incurred the greatest risk. Combining participants with little phone use with those with heaviest use diluted the chances of finding any effect.

The case-control MobiKids study of 352 brain cancer patients between the ages of 10 to 24 reported cell phone use; it also found no overall increased risk for brain tumors in the age group diagnosed between 2010 and 2015. The latency for brain cancer in adults is known to range up to four decades; in children it is believed to be shorter. In fact, only 5% of the study participants—17 individuals—had used cell phones for more than 5 years. Unsurprisingly, no evidence of significant association emerged. This study has also been criticized as methodologically flawed[156] especially as so few of the participants had significant exposures to cell phones. Although no overall increased risk was reported for brain tumors in the temporal region of these young cases an increased risk was found in the age groups 10–14 and 20–24 years—age groups that had lived long enough to have incurred more exposure than the younger children included in this study.

Despite major limitations in design, the Mobikids study of cell phone use in Canadian children reported a doubled risk of glioblastoma multiforme from using cell phones, a risk that should provide a sobering message to those that seek to prevent such disease from occurring in the first place.

Researchers examining the Canadian MobiKids cohort carried out sophisticated statistical modeling including potential sources of biases and probabilistic methods, and did not find strong evidence of an association between reported cellphone use and meningioma, acoustic neuroma, or parotid gland tumors—tumors plausibly linked with cell phone radiation, but they did note a significant association with glioma.

For glioma, when comparing those in the highest quartile of use (>558 lifetime hours) to those who were not regular users, the odds ratio among Canadian children participating in Mobikids was 2.0 (95% confidence interval: 1.2, 3.4). After adjustment for selection and recall biases, the odds ratio was 2.2 (95% confidence interval: 1.3, 4.1).

Despite major limitations in design, the Mobikids study of cell phone use in Canadian children reported a doubled risk of glioblastoma multiforme from using cell phones, a risk that should provide a sobering message to those that seek to prevent such disease from occurring in the first place.

More recent case-control studies of glioma in adults from Sweden[157] and France,[149] and systematic analyses that combine data on adult cell phone users carried out in China find 10 years or more of cell phone use significantly associated with increased risk of glioblastoma, with 20 years of exposure resulting in a more than doubled risk. Analyses of shorter-term exposures, such as predominated in the Interphone study, do not find such an association, suggesting that there is a latency of 10 years or more for glioblastoma. Thus, in those few studies that have followed longer term users, more hours of use and longer time periods of use have been found significantly associated with between a 40% to more than 200% increased risk of glioblastoma.

Cancer epidemiology—Cohort studies

In contrast to case controls studies, the UK 'Million' Woman Cohort study and the Danish Cohort Study constitute two studies often cited as proof that there is no relationship between cell phone use and brain cancer. Both have been roundly criticized for serious shortcomings. For example, in the UK cohort study of almost 800,000 older menopausal women, only 18% of cell phone users[158] talked 30 or more minutes per week, as self-reported from 2001 to 2011. Yet, the U. K. study combined slight and regular mobile phone users into a single category and compared them with those who reported no phone use. More than 80% of UK households had landlines during the study period. It is likely many in this cohort also used cordless phones, yet, this significant additional source of RF was not evaluated. In fact, the UK cohort authors acknowledge[159] their study was unable to assess the risks associated with considerably greater levels of exposure. Consequently, the authors note that: "advising heavy users on how to reduce unnecessary exposures remains a good precautionary approach."

Other cancers plausibly reported in epidemiological studies to be tied with cell phone radiation include: thyroid cancer, early-onset breast cancer, early-onset colorectal cancer, and testicular cancer. In a certain subset of those with a common genetic susceptibility, heavy cell phone usage is associated with significantly doubled risk of thyroid cancer.[69] Since the advent of smart phones in 2010, phone antennas tend to be located at the bottom of phones As a result, peak phone RFR exposure is more likely to occur in the neck than in the brain.[160] Smart phones include several different antennas, each one of which can send and receive RFR, with multiple antennas for data, photos, video and other applications located around the phone perimeter. In addition, women who have carried phones in their bras or worn Vocera devices next to their chest have developed unusual patterns of breast cancer, with tumors sometimes appearing precisely under the areas where their phone antennas were located.[161,162]

In those few studies that have followed longer term users, more hours of use and longer time periods of use have been found significantly associated with between a 40% to more than 200% increased risk of glioblastoma.

Several independent analyses published since the original IARC assessment in 2011 conclude that if the criteria that the WHO/IARC relied on when determining carcinogenicity were applied to current science, this would result in classification of cell phone radiation as a probable carcinogen (Group 2A) or proven (Group 1) human carcinogen.[7,8,16,163–167]

Unexplained increases in pediatric and young adult cancers are consistent with increasing wireless exposures

Trends in cancer can provide signals about underlying etiologic factors, as occurred with increases in lung cancer in male and female smokers in the mid-twentieth century, and increases in the rare clear-cell adenocarcinoma of the cervix in young women whose mothers had used diethylstilbestrol to prevent miscarriage.[168] Cancers tend to have multiple contributory causes, which can ebb and flow over time. Over the last several decades, incidence of several different early-onset cancers in adults[169] below 50 years of age have increased in many nations, including those of the breast, colorectum, bone marrow, and thyroid. Although explanations for these patterns will certainly be multi-factorial, wireless radiation is one of the factors that should be more widely explored.

Rates of rectal cancer have quadrupled in those under age 24 in the past decade in the U.S. and Iran and risen rapidly[170] in the U.K, Egypt, and Brazil. One recent study[171] asserts that these increases could, in part, be associated with radical changes in exposures to cell phone radiation due to devices kept close to the body for extended periods of time. More and more children and young adults keep transmitting smartphones with their multiple antennas that are constantly updating apps next to their abdomens inside their tight clothing for hours a day, along with a wireless earpiece in their ear. Thus, although speaking directly into phones has declined, close proximity to their radiation has not.

What makes the potential connection between colorectal cancer increases and cell phone exposures especially plausible is an experimental study showing that colon and rectal cells are exquisitely sensitive to non-ionizing radiation like that emitted by phones today. Moreover, exposure to non-ionizing mobile phone radiation can lead to effects on treated colon tissues of rats similar to those observed from ionizing 3Gy gamma radiation. Mokarram et al.[172] reported that epigenetic patterns of the estrogen receptor (ERα) after exposure to ionizing radiation paralleled those occurring after exposure to non-ionizing RFR. Using biomarkers that have previously been established to signal damaging exposures, they further found that methylation patterns may constitute an important validated biomarker of exposure to radiofrequency radiation that has the potential to play a role in the expression and promotion of colorectal cancer.[172]

RFR has all the classic hallmarks of endocrine disruptors that affect reproduction, development of the hypothalamic-pituitary-gonadal axis (HPG) and alter normal male and female reproductive endpoints.

EMFs as endocrine disruptors

Endocrine disruptors are understood to be agents, either natural or man-made, which can mimic or interfere with the body's hormones and disrupt development leading to a range of developmental, reproductive, neurological, and immune problems, as well as cancers. Common sources include plastics, metal can liners, detergents, flame retardants, and pesticides.

EMF exposures have been linked to a range of classical endocrine disrupting effects.

A team from the California Institute of Behavioral Neurosciences & Psychology reviewed the effects[173] of both RFR and ELF on thyroid gland hormones and histopathology and found evidence that RFR was associated with alterations in T3, T4, and TSH hormone levels, disruption of the function of the HPG axis leading to thyroid insufficiency and hyper-stimulation of thyroid gland follicles. This caused apoptosis of follicular cells. Non-ionizing radiation was seen to be significantly associated with histopathological changes in the thyroid gland follicles and the authors contend that non-ionizing EMF radiation might be responsible for the recent increase in the incidence of thyroid insufficiency and cancer in the general population.

Critical research needs to be conducted to understand the effects especially to future generations. Cantürk et al.[174] investigated the effects of pre- and postnatal 2450 MHz RFR on the thymus of rats over four generations and found that the number of pups and weight of all rats decreased significantly in the third-generation.

Thus, it appears that non-ionizing [175] RFR has all the classic hallmarks of endocrine disruptors that affect reproduction, development of the hypothalamic-pituitary-gonadal axis (HPG) and alter normal male and female reproductive endpoints. Alterations in spermatogenesis and oogenesis, for example, in turn affect a number of endocrinological and other functions throughout life, including fertility and behavior in offspring along with the risk of cancer, neurological disorders and other chronic illnesses.

Animal studies of additive or synergistic effects of RFR with other agents

Replicated experiments show that RFR can have important co-carcinogenic and tumor promoting effects when combined with known carcinogens. Lerchl et al.[152] found carcinogen-induced tumor rates were significantly higher in mice exposed to nonthermal doses of radiofrequency below current regulatory limits. The authors argued that it was a "very clear indication that in principle tumor-promoting effects of life-long RFR exposure may occur at levels supposedly too low to cause thermal effects."

The Ramazzini Institute performed two large lifespan rat cancer studies[176] combining magnetic field non-ionizing EMF with either acute exposure to gamma radiation or chronic exposure to formaldehyde in drinking water and found significantly greater incidence of malignant tumors with either co-exposure than occurs without such combined exposures.

Investigators from the Beijing Institute of Radiation Medicine in China have also produced important evidence of synergistic effects. They determined that combining 2.8 GHz and 1.5 GHz microwaves[177] impaired spatial memory much more strongly than exposures to a single frequency. It is important to realize that such combined frequencies can easily occur at this time within a single smart phone that can operate on different frequencies at the same time. This same team has reported[178] that exposure to nonthermal levels of 2.8 GHz and 9.3 GHz—as could occur with 5G networks– led to significant impacts to the thymus and spleen, such as congestion and nuclear fragmentation of the lymphocytes, and more severe injuries. Their transcriptomic and proteomic analysis of peripheral blood and spleen suggested that alterations of DNA replication, cellular metabolism, and signal transduction might be involved in microwave-induced immune activation. The spleen not only filters blood-borne pathogens and antigens but also plays a critical role in immune system regulation.

Higher levels of adolescent screentime,[179] social media access[180] and cell phone use in teenagers' bedrooms are associated with reduced sleep time[181] as well as negative effects on daily functioning,[180] behavior[182] and mood.

Effects of screen time

Higher levels of adolescent screentime,[179] social media access[180] and cell phone use in teenagers' bedrooms are associated with reduced sleep time[181] as well as negative effects on daily functioning,[180] behavior[182] and mood. An ever growing body of evidence[183] is associating[184] children's addictive and excessive use of screens and digital media with a myriad of adverse social (relationships, social skills, cyberbullying), psychological (anxiety, depression, suicidal ideation, obsessive compulsive disorder[185]) neurodevelopmental (cognitive development, behavior, attention, speech[186]) and physical (obesity, high blood pressure) consequences. Key factors[187] determining screen time effects include duration, content, media type, degree of access to social media, whether screens are located in the bedroom[180] and the amount of after dark/evening use.[180,187]

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Axelsson et al.[188] found the amount of time spent with screens predicted shorter sleep in preschoolers. Regardless of the time of day that screens were accessed by children, greater screen time was associated with poorer sleep quality, poor communication, poor problem solving and greater attention problems. The AAP notes,[184] "the prevalence of problematic Internet use among children and adolescents is between 4% and 8%.

Up to 8.5% of U.S. youth 8 to 18 years of age and 4.6 % of Chinese youth meet criteria for Internet gaming disorder defined by the World Health Organization in its standard Diagnostic and Statistical Manual of Mental Disorders-Fifth Edition (DSM-5) as an uncontrollable, persisting need to engage directly with digital media and games that cannot be stopped.

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This diagnostic code is included in the DSM-5,[189] and in the 11th Revision of the International Classification of Diseases (ICD-11[6]), signaling interference with socialization, including disturbing important areas of life such as family relationships, school, work, eating, bathroom habits and sleep. In its criteria for gaming disorder, the WHO does not include in its criteria any specific number of hours spent with screens, but instead focuses on the inability to engage in normal social life of young children and teens, including outdoor activities as well as socializing indoors with family and at school. The category of internet gaming disorder was added in 2019. According to Pew,[190] 97% of teen boys and 83% of girls play games on some kind of device. How many of them are addicted is a matter that should be seriously examined, as the toll on pediatric mental and physical health continues to mount.

Higher screen time has been associated with a higher prevalence of prospective disruptive behavior disorders.[191] Clinicians[187,192] posit that the effects of electronic screen time can mimic or exacerbate psychiatric disorders as the interactive media can lead to chronically high arousal levels which can lead to nervous system dysregulation. As a consequence, treating physicians have developed treatments including an "electronic fast" to rebalance the brain and relieve overstimulated reward (addiction) and sensory pathways. Interventions such as reducing screen media have been found to result in a substantial increase in children's engagement in physical activity[193] and increasing outdoor "green" time[194] is beneficial to mental health as well as lowering myopia incidence[195] in school-aged children.[196]

Technoference contributes to speech and bonding delays

Studies[116] of infant parental dyads find that more frequent reported mobile device use was associated with less room exploration and positive affect, and less recovery (i.e., engagement with mother, room exploration positive affect) even when controlling for individual differences in temperament. Delays in speech acquisition[197] and the development of interactive skills also have been reported in infants of parents that use devices more frequently. In addition, the phenomenon of "technoference"[198] is receiving increased attention from experts in behavioral and development psychology. Heavy parental digital technology use has been associated with suboptimal parent-child interactions. Parental problematic technology use—termed "technoference" — is associated with technology-based interruptions in parent-child interactions and potentially associated with a range of child behavior problems.

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Parental distraction in early infancy can be problematic for obvious reasons. This remains a topic of increased research attention and a matter that should be routinely queried at every well child visit, beginning with infancy throughout the school years. Simple questions noted below can provide the foundation for teachable moments that convey the need for direct parental involvement in early years when lifelong benefits can accrue. Harried young parents, especially those who are raising children without partners, may rely heavily on digital devices as a form of childcare. They should be informed about the importance of direct eye and verbal contact with infants, as well as reading aloud starting in infancy, as these practices have been shown to have lifelong benefits to social and emotional development.

Clinical practice guidance

Avoidable environmental exposures can profoundly affect and alter children's development and health. Along with the benefits of nutrition and regular physical and social activity, clinicians are aware of adverse effects of lead, pesticides, food additives, air pollution, ultraviolet radiation, and more broadly climate change, on children's health. Exposures that take place early life can have disproportionately large impacts on later life health and well-being.

As recommended by the AAP, clinicians can integrate developmental as well as EMF issues in practice by regularly discussing screentime and digital media use. AAP guidance regarding phones and other wireless devices should be widely shared and employed. These include:

- For children under 18 months, avoid screen-based media except video chatting.
- For children 18 months to 24 months, parents should choose high-quality programming and watch while interacting with their children, on a limited basis.
- For children 2 to 5, no more than one hour per day of high-quality screen time and engage with children regarding content and experiences.
- For children 6 and up, establish consistent limits on the time spent using media and the types of media.

Recognizing that RFR may contribute to ill health provides further incentive to include clinical practices such as:

- Query use of screens, digital media, cell phones and Wi-Fi linked devices at yearly physicals;
- Provide guidance to patients and their families on how to decrease excessive screen time and to reduce RFR exposure (See Section 7);
- Respond with additional interview questions, resources and referrals as appropriate if symptoms potentially related to use of screens or exposure to EMFs are reported;
- Engage in continuing education and training on EMF issues, and screen use;
- Record and report cases where links have been identified between EMF and symptoms or health outcomes;
- Encourage undistracted reading out loud to infants and young children; and
- Develop family media plans for parents as well as children, explaining that parental distraction with devices can impair child development including speech acquisition.

Practitioners also need training in EMF-related effects to be able to discern whether common pediatrics complaints such as headaches and problems sleeping could, in fact, be due to the excessive use of technologies in the home or school environment. Clinicians encountering patients presenting with unexplained symptoms can consider the complete clinical picture and health history, and investigate, treat if necessary, or exclude commonly recognized etiologies. For example, patients may come into the office with unexplained array of symptoms such as headaches and rashes that may be related to EMF (e.g., cell antennas recently mounted nearby, or upgraded school Wi-Fi system recently installed). Clinicians need greater awareness so that in differential diagnosis they include the possibility that symptoms may be associated with EMF and evaluate the patient in a systematic fashion.

Clinical practice guidelines for EHS have been developed by trained clinicians and experts,[199] EUROPAEM group,[200] Dr. Riina Bray, Medical Director, Environmental Health Clinic, at Women's College Hospital, University of Toronto[201] and the Austrian Medical Association,[202] among others.

Clinical practice guidelines include:

- Comprehensive case history that includes environmental exposure history including questions regarding typical daily EMF/ RFR exposure, toxic metal exposures, diet, mold, and other potentially toxic chemical exposures at home, child care settings, school, work and play, and in the community.
- Assess community, work, school and home exposures to EMFs: proximity of cell phone towers, routers, DECT cordless phones, and any other wireless technology, especially in sleeping areas
- Assess variation of health problems depending on time and location. For example, do headaches or other unexplained symptoms attenuate in different areas, but return chiefly when the child is in one specific location? Did headaches or symptoms begin when a new router or cell antenna was installed?

As technologies (and healthier alternatives) evolve and knowledge advances, there is a need for clinicians periodically to update their knowledge through continuing medical education with technical experts in bioelectromagnetics—a field that is not widely taught or studied in medical schools at this juncture. Some accredited programs[203] offering up to 24.5 continuing medical education credits can be found online.

Electromagnetic sensitivity—An underdiagnosed pediatric problem

The phenomenon of hyper-reactivity to chemical and physical phenomena remains poorly understood but is believed to be a serious and sometimes disabling problem.

Electromagnetic hypersensitivity (EHS)[204] is believed to affect a small but significant segment of the population—with estimates up to 15%. Its prevalence in children has never been evaluated, but could prove to be important in cases in which vague symptoms of headache, numbness, tingling and rash cannot otherwise be alleviated. EHS is characterized by headaches, sleeping problems, memory problems, nosebleeds, unexplained skin rashes, digestive problems, neurological problems, heart palpitations and fatigue. Symptoms[200] vary from person to person, making this a challenging subject to study and to treat. Notably, prenatal and postnatal exposure to cell phone RFR is linked to increased headaches in children,[205] adolescents,[206] and adults,[205] and use of smartphones have been identified as a trigger for migraines.[207]

EHS symptoms[208] have been linked to exposures to non-ionizing EMF, including from nearby cell towers and base station wireless antennas and routers. No studies have been conducted on EHS in children. Dieudonné[209] studied forty individuals convinced that they were sensitive to electromagnetic fields, and concluded that contrary to allegations of nocebo responses, attribution of their symptoms followed a common linear model: (1) onset of symptoms; (2) failure to find a solution; (3) discovery of EHS; (4) gathering of information about EHS; (5) implicit appearance of conviction; (6) experimentation; and (7) conscious acceptance of this knowledge.

The U.S. Access Board[211] has recognized that "electromagnetic sensitivities may be considered disabilities" under the Americans with Disabilities Act, and the Job Accommodations Network supported by the U.S. Department of Labor's Office of Disability Employment Policy has issued a list of guidelines[212] for accommodation of electromagnetic sensitivity.[213]

Further evidence of the importance of identifying sources of exposure and reducing them comes from a recent report from Sweden on the sudden acquisition of highly reactive biological responses to a newly introduced source of RFR. Following the introduction of 5G networks in a dense urban environment, a previously healthy couple reported disabling symptoms of headache, palpitations, tingling, tinnitus and major discomfort. Upon detailed examination of their environment, it was determined that 5G network had recently been installed quite close to their apartment. A thoroughly detailed case report[210] documents this sudden change in RF exposure and the onset of severe symptoms in this couple just a few days after the installation of a 5G base station on the roof above their apartment. The deployment of 5G caused a dramatic increase in maximum (peak) microwave radiation exposure, from 9 000 μW/m2 to >2 500 000 μW/m2. The symptoms quickly reversed when the couple moved to a dwelling with much lower exposure.

Symptoms often are misdiagnosed as health professionals lack training on the matter. Preliminary clinical practice guidelines[201] have been developed. The U.S. Access Board[211] has recognized that "electromagnetic sensitivities may be considered disabilities" under the Americans with Disabilities Act, and the Job Accommodations Network supported by the U.S. Department of Labor's Office of Disability Employment Policy has issued a list of guidelines[212] for accommodation of electromagnetic sensitivity.[213] Adults in the U.S. are often accommodated in the workplace (being provided hardwired computer connections, or moving to a lower-EMF office) but in many cases they have had to file legal actions.

Despite these accommodations for adults, parents seeking accommodations in U.S. public schools for children who experience EHS have been challenging as schools will refuse to accommodate and the families often must resort to homeschooling. In the UK, parents won a legal battle[214] against local authorities who are now compelled to provide an environment with reduced wireless radiation so that their child can attend school. There are also other examples internationally of legal decisions mandating workplace accommodations or payment for injuries[215] from EMF exposure.

In Canada, EHS is described in the report, Medical Perspectives on Environmental Sensitivities[216] to the Canadian Human Rights Commission.[217] Medical and legal[216] reports underpin a policy[218] for accommodation under the *Canadian Human Rights Act.*

Synergistic and combined toxic exposures in children

Children are exposed to numerous combinations of environmental exposures over their lifetime. Even where exposures are low, they can interact with each other resulting in additive or synergistic results.

Animal and human studies[219] indicate that non-ionizing EMF can act synergistically when combined with other toxic agents. For example, Sueiro-Benavides et al.[220] found that 2.45 GHz, a frequency used in Wi-Fi networks, combined with carbon black (CB) increased CB-induced toxicity and prolonged inflammatory immune responses. Exposures to non-ionizing EMF from magnetic resonance imaging (MRI) or cell phones has been found to enhance the release of mercury from dental amalgam.[221] RFR has been found in several studies to impact the integrity of the blood-brain barrier that protects the brain from toxic molecules circulating in the blood.[132,222–225]

A longitudinal study[226] of 2,422 children at 27 elementary schools in 10 Korean cities examined effects and interactions between voice call cell phone use and blood lead levels (lead levels were comparable to those in U.S. children). Attention-deficit/hyperactivity disorder symptom risk was significantly greater in the children with above-median lead levels and above-median weekly cell phone call duration.

A similar interaction was reported by Choi et al.[227] Across the cohort, maternal cell phone use during pregnancy was not associated overall with child neurodevelopment during the first three years. Among children exposed to higher maternal blood lead level *in utero*, however, a greater risk of both a poorer psychomotor development index and a lower mental development index up to 36 months of age was associated with higher cell phone calling time or frequency during pregnancy.

A theoretical role for RFR in the etiology of autistic spectrum disorder

Autism remains a puzzling and troubling problem for growing numbers of children, their families and their physicians. The disease[228] is increasing among both males and females, and among nearly all racial/ethnic subgroups, from 4.2 per 1,000 in 1996 to 15.5 per 1,000 in 2010. A recent report from the U.S. Centers for Disease Control and Prevention notes that rates have continued to increase. The prevalence of autism spectrum disorder (ASD) among 11 surveillance sites is 1 in 54 among children aged 8 years in 2016 (or 1.85%). This constituted a 10% increase from 2 years previously when it was 1 in 59, and the highest prevalence since the CDC began tracking ASD in 2000. Consistent with previous reports, boys were 4 to 5 times more likely to be identified with ASD than girls. The rate for ASD is 1 in 34 among boys (2.97 percent) and 1 in 145 among girls (0.69%). Although many environmental factors[229] have been posited, including air pollution, pesticides, and heavy metals, the potential role of RFR should also be seriously explored.

Experimental studies showing that prenatal exposures to RFR can disrupt the development of the hippocampus provide some foundation for speculating that EMFs could also be a contributing factor. Thus, RFR has plausibly been hypothesized to play a role in the development of ASD via disruption of the developing poorly myelinated central nervous system. When presented with serious behavioral disorders including autism, some psychiatrists have employed successful treatment protocols that involve family management systems to facilitate cessation and withdrawal from use of digital devices. Psychiatrist Victoria Dunckley[192] notes that early use of digital devices can create a heightened state of fight or flight among young brains and bodies, placing them under constant stress. Children are easily addicted to routines of falling asleep, eating and even using the toilet accompanied, not by parents soothing assurances, but by digitized music, visions and sounds that increase dopamine—the brain chemical tied with pleasure and addictive behaviors. Providing several impressive case reports of toddlers that had been out of control and unable to give up their digital fixations, Dunckley notes that digital fasting can yield impressive results, especially with children on the autism spectrum. Her book provides several detailed instances where altering children's access to digital devices can radically improve behavior. Other published reports also offer corroboration for this hypothesized connection.[230,231]

Psychiatrist Martha Herbert and research analyst and editor of the *Bioinitiative Report*, an ongoing record of relevant scientific findings, Cindy Sage, among others, have called for more aggressive investigation of the possible connections between RFR uses and exposures and disorders on the autism spectrum. They speculate that behaviors on the autism spectrum could emerge from alterations of electrophysiological oscillatory synchronization and EMF/RFR could contribute and "worsen challenging biological problems and symptoms; conversely, reducing exposure might ameliorate symptoms of ASD by reducing obstruction of physiological repair."[232,233]

Inadequate regulatory limits

FCC and ICNIRP regulatory limits have been long criticized by experts and the court because they do not address children's unique vulnerability, the biological and health effects of long-term exposure nor the current ways that children are exposed to cell phone and wireless radiation. In 2012, the AAP wrote the FCC and other federal agencies calling for an update to the FCC's 1996 exposure limits stating, "it is essential that any new standard for cell phones or other wireless devices be based on protecting the youngest and most vulnerable populations to ensure they are safeguarded throughout their lifetimes." A decade later that call remains unanswered.

Cell phone and wireless device limits

Regulations regarding human exposure to RFR include: 1. allowable limits for ambient exposures created by cell tower network emissions and wireless networks, called maximum permissible exposure limits in the U.S.; and 2. exposure limits for localized exposures into areas of body tissue from phones, and personal and household devices, referred to as Head and Body SAR limits. The ICNIRP and IEEE[38] standards used as the basis for many governments' limits remain largely unchanged since the 1990s and they are intended to protect for effects caused by short term high powered exposures. These limits are not designed to protect for effects from long term, low level chronic exposures because ICNIRP and IEEE do not consider such effects as "established." As former ICNIRP member James C. Lin describes them: "*They are flawed and are not applicable to long-term exposure at low levels. Instead of advances in science, they are predicated on misguided assumptions with outdated exposure metrics that do not adequately protect children, workers, and the public from exposure to the RF radiation or people with sensitivity to electromagnetic radiation from wireless devices and systems. Thus, many of the recommended limits are debatable and absent of scientific justification from the standpoint of safety and public health protection.*"[16]

Wireless network exposure limits

U.S. limits for RFR were promulgated by the FCC in 1996, based largely on a 1986 Report of the National Council on Radiation Protection & Measurements (NCRP)[234] and the Institute of Electrical and Electronics Engineers (ANSI/IEEE) C95.1-1991 standard.[235] The U.S. limits for environmental RF levels are among the most lenient in the world, and are similar to those of Australia, Japan, Germany and other countries that also adopted inadequate ICNIRP limits.

However, some countries, including Italy, Switzerland, China, and Russia have adopted regulatory limits for cell towers and base station network emissions that are far more stringent[236] than the thermally based limits of the U.S. FCC and ICNIRP.

European nations with more stringent regulatory limits set their policies based on the precautionary principle, a key framework used in their decision making process. This principle rests on the sage advice of Benjamin Franklin—better to be safe than sorry.

In 2011, the Parliamentary Assembly of the Council of Europe (PACE) Resolution 1815: The potential dangers of electromagnetic fields and their effect on the environment "[237] strongly recommends that the ALARA (as low as reasonably achievable) principle is applied, covering both the so-

In 2011, the Parliamentary Assembly of the Council of Europe (PACE) Resolution 1815: The potential dangers of electromagnetic fields and their effect on the environment "[237] strongly recommends that the ALARA (as low as reasonably achievable) principle is applied, covering both the so-called thermal effects and the athermic or biological effects of electromagnetic emissions or radiation."

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In contrast, the more strict RF limits in Russia and China[238] are considered "science based," not precautionary, and were developed based on their own government scientists' studies of the biological effects of nonthermal RFR levels. India lowered its limits to 1/10 of ICNIRP limits in 2012[239] in response to a report from an Inter-Ministerial Committee that reviewed the research[240] on impacts to wildlife, including honeybees and other pollinating insects, and concluded[239] that the "vast majority of published literature indicate deleterious effects of EMFs in various species." (See Fig. 7 for comparisons) It is notable that other groups have recommended even lower limits. For example, the Ecolog Report, commissioned by T-Mobile and Deutsche Telekom in 2000, reviewed the science recommended a limit of 0.01 W/m2 to" be rigorously adhered to by all base stations near sensitive places such as residential areas, schools, nurseries, playgrounds, hospitals and all other places at which humans are present for longer than 4 hours."[241]

Why the SAR standard is inadequate to protect children

Pre-market tests for cell phones and wireless devices measure the Specific Absorption Rate (SAR), which is the standard accepted measurement of the rate of RF (radiofrequency) energy absorption. (See Table 2.) For cell phones and other handheld wireless devices, many countries have adopted either FCC or the ICNIRP limits for premarket RF compliance. Although the FCC limit is slightly more restrictive compared to ICNIRP limits, both rest on avoiding the effects of heating as measured by the SAR.

The SAR metric is criticized as a heat-based measure unable to capture[72] the numerous characteristics[242] of nonthermal exposure considered relevant to bioeffects such as pulse, modulation, variability or duration of exposure.

That said, even if the SAR was a valid measure for health effects thresholds, the SAR testing protocol itself has long been criticized as unrealistic for numerous reasons. To start, it does not take into account the smaller sizes of women, infants and children, and other properties of children that place them at greater vulnerability. Thus, the child brain sits in a thinner skull that contains more fluid which can absorb more radiation per unit volume than the adult brain with its thicker skull.

In regards to children's exposure, the AAP[1] wrote the FCC in 2012 noting that, "although wireless devices sold in the United States must ensure that they do not exceed the maximum allowable SAR limit when operating at the device's highest possible power level, concerns have been raised that long-term RF exposure at this level affects the brain and other tissues and may be connected to types of brain cancer, including glioma and meningioma," and also that, "The current metric of RF exposure available to consumers, the Specific Absorption Rate, is not an accurate predictor of actual exposure."

The head and body phantom are filled with a homogenous liquid that does not capture the way the electromagnetic field moves through different tissues in the head such as brain tissue, which is of varying thicknesses and characteristics. The dielectric properties of tissues in children's head and brain differ from adults because children's tissues have more water content and thus are more conductive than adults.

The SAM model has long been argued to provide a conservative estimation of the exposure from a mobile phone, even for children. However, research supporting this position has generally used a scaled down version of an adult head which did not account for all age dependent variations in children, such the anterior fontanels which close between 7 and 18 months. When these more realistic variations are accounted for, the SAR values for children are significantly higher. For example, Mohammed[243] used realistic head models in several scenarios simulating young children between 3 months and 18 months holding phones near their ear and mouth as well as a person holding a mobile phone near a child's head. They found that 10g SAR values in the heads of young children are significantly higher than those for adults and also noticeably higher than the scaled models used in previous studies that considered dosimetry for children over 3 years old.

Research supporting the SAM model[244] is based on early phone models that were designed with antennas on the top of the phone body and more recent research has found that for newer phone models with antennas integrated along the bottom of the phone, the SAM does not always ensure[40] a conservative estimation.

Phones are tested while operating at the highest power level, in specific positions against the phantom head and body. Devices generally operate at the minimum necessary power, in order to maximize battery life, but in many situations the power output is much higher, to ensure reception at the receiving antenna in the cellular base station. Low incoming signal strength triggers a significant increase a phone's emissions; people encounter low signal strength in rural areas far from base stations and also, for example, in rooms in basements or buildings where building materials block the signal. The many real world exposure scenarios result in highly variable emissions from any one cell phone model, regardless of the stated SAR value.

Although the standardized SAR test positions are supposed to simulate the way people typically hold a cell phone, the standardized positions do not test in body contact positions for body SAR tests. The test positions do not mimic a cell phone in full body contact such as in a pants pocket or resting against the abdomen. Parents today often hold their newborns with the cell phone right up against the baby and yet premarket SAR tests do not include such positions.

In summary, the SAR test and SAM have been roundly criticized as underestimating and not adequately capturing the real world exposures of children, babies, and toddlers, and children who are positioned in direct or close body contact with cell phones or other devices.

Furthermore, manufacturers SAR test phones at various distances from the body. In the U.S. a manufacturer can decide to test for body SARs at 5, or 10, or even 25 mm. The measured SAR value will increase the closer the phone is tested to the body phantom. Thus, the manufacturer posted SARs of different models that use different separation distances cannot be directly compared to each other.

Although SAR levels often are used to compare cell phones in terms of which phone emits more RF than others, the SAR value does not necessarily reflect a difference in a consumer's actual exposure for these reasons. Hence a phone with a lower SAR level does not necessarily mean lower RF exposure. Nonetheless, the SAR is the metric in use and the basis for exposure limits worldwide.

Regulatory gaps affecting children

The AAP[1] has long advocated[1] that federal agencies strengthen regulations calling for:

- A reassessment of human exposure limits and testing requirements to ensure children's unique vulnerabilities are addressed and to reflect the way children use phones today in close proximity to the body;
- Establishing a federal research program as the basis for exposure standards;
- Cell phone and wireless device product labeling requirements to "enable parents to better understand the potential dangers of RF energy exposure and protect their children."

The AAP supported[245] national legislation, the Cell Phone Right To Know H.R. 6358,[246] proposed in 2012, which would have addressed numerous regulatory gaps in federal policy regarding stating that, "Children are disproportionately affected by environmental exposures, including cell phone radiation. The differences in bone density and the amount of fluid in a child's brain compared to an adult's brain could allow children to absorb greater quantities of RF energy deeper into their brains than adults."

Prevention: medical organization, public health, government policy and actions to mitigate risk to children

Based on the established science, including children's special vulnerabilities, trajectories of exposures and diseases, clinicians need to know that they are supported by medical associations, have the resources to support their patients, and finally have the evidence in hand to advocate for them. A few of the supportive agencies and recommendations are noted below. Others can be found at www.ehtrust.org.[247]

Medical organizations and public health agencies

The AAP and several international medical organizations[248–251] have recommendations[252] on how to reduce cell phone radiation exposure. The AAP has long advocated for more protective[245] federal regulations and issued ten ways to decrease exposure in 2016[252] including "avoid carrying your phone against the body like in a pocket, sock, or bra. Cell phone manufacturers can't guarantee that the amount of radiation you're absorbing will be at a safe level."

"Avoid carrying your phone against the body like in a pocket, sock, or bra. Cell phone manufacturers can't guarantee that the amount of radiation you're absorbing will be at a safe level." American Academy of Pediatrics.[252]

In 2017, the California Department of Public Health (CDPH) released an advisory on cell phones.[253] CDPH's scientists had evaluated the RFR from almost[254] two dozen phones and found that when they transmit at their highest power due to use in areas of low service (one or two bars) the emissions can be up to 10,000-fold higher than when the phone is used in areas of strong signal. The CDPH's advice initially was based on the University of Pittsburgh Cancer Institute's 2008[253] cell phone radiation reduction advice to doctors and staff, constituting the first ever U.S. medical institution advisory on cell phone radiation.

> ***"Avoid carrying your phone against the body like in a pocket, sock, or bra. Cell phone manufacturers can't guarantee that the amount of radiation you're absorbing will be at a safe level." American Academy of Pediatrics.[252]***

In 2022, the Maryland State Children's Environmental Health and Protection Advisory Council[255] issued information on how families can reduce wireless and non-ionizing EMF exposures at home and also made recommendations to schools.

A summary of basic recommendations from these organizations and agencies is presented below.

How families can reduce EMF exposure

Cell phones

- Cell phones are not toys or teething items.
- When parents hold their babies or children in their arms, they should not simultaneously use or hold mobile phones or wireless devices as this will expose the child to RFR.
- Decrease overall time spent on wireless phones and prefer corded phones for long calls.
- Delay purchasing a first cell phone for a child. Cell phones should only be used by children for emergencies.
- Prefer text messaging over voice and video calls.
- Decrease exposure to and through the brain by using cell phones in speaker mode, away from the head and body, or wired airtube headsets with the phone away from the body. Avoid airpods. While Bluetooth signals are much weaker than cell phones, children and teens keep them in their ears for hours a day and the long term impact has never been independently evaluated.
- Avoid carrying cell phones against the body like in a pocket, sock, or bra.
- Do not talk or text while driving.
- Learn how to switch phone to airplane mode with Bluetooth, Wi-Fi, Hotspot antennas toggled off in settings. Many applications on phones can still be utilized in airplane mode. For example, in order to play movies and music but avoid unnecessary RFR exposure, download the files first, then switch the device to airplane mode and play.
- Keep an eye on your signal strength (i.e. how many bars you have). The weaker your cell signal, the harder your phone has to work and the more radiation it gives off. It's better to wait until you have a stronger signal before using your device.
- Avoid making calls in cars, elevators, trains, and buses. The cell phone works harder to get a signal through metal, so the power level increases.
- Learn how to connect the cell phone to the internet with ethernet cables.

Computer, laptop and tablet internet connections in buildings

- Install internet access via a hardwired ethernet connection instead of Wi-Fi.
- Wi-Fi routers should be distanced from areas where children sleep, play and school.
- At a minimum, power Wi-Fi networks off at bedtime and during periods when not in use.
- Connect computer/laptop/tablet accessories and peripherals such as printers, speakers, keyboard and mouse with cords, rather than Wi-Fi or Bluetooth.

At home

- Replace cordless phones with corded phones. Cordless phones and their base stations emit RFR.

- Avoid wireless digital baby monitors. If necessary, choose wired monitoring systems.
- Remove screens, electronics and wireless devices from the bedroom.
- Turn off devices at night and ensure sleep areas are not against a wall where utility meters are installed on the other side as "smart" meters are sources of RFR and other EMF.

Additional considerations during pregnancy

Simple preventive measures during pregnancy can significantly decrease fetal exposures, especially the high intensity exposures from a wireless device resting directly on the abdomen.

- Distance cell phones and wireless devices away from your abdomen.
- Power off cell phones when carrying them near your body.
- Always use laptops and tablets on a desk, not on your lap or close to your abdomen.
- For voice calls, use corded phones instead of cell phones or cordless phones.
- Use ethernet connections instead of Wi-Fi to connect devices.

Several governments, such as France, Israel, Greece and Switzerland have RFR measurement programs in place along with easy access to the data. For example, in France, the National Frequency Agency ANFR "Observatoire des Ondes"[257] posts online the RFR measurements taken numerous times a day in various cities.

Cell tower emission and ambient limits

As shown in Fig. 7 numerous countries such as India, Israel, Greece, China,[256] Russia and eastern European countries have RFR limits for cell tower network emissions that are much stricter than the limits of the US/FCC (although there is not always documented reliable monitoring or enforcement in every country). Australia, Japan, Italy and Switzerland have limits for areas such as schools and apartment buildings and areas where people spend several hours a day. Several governments, such as France, Israel, Greece and Switzerland have RFR measurement programs in place along with easy access to the data. For example, in France, the National Frequency Agency ANFR "Observatoire des Ondes"[257] posts online the RFR measurements taken numerous times a day in various major cities. Countries such as Greece and Israel have policies in place that specifically restrict the placement of cell towers near "sensitive areas" defined generally as schools and/or homes and hospitals and provide for online access to real-time radiation levels. Greece further restricts exposure to a stronger limit within 300 m of sensitive areas. Chile's "Antenna Law"[258] has established mitigation measures in areas with dense infrastructure and prohibits towers near "sensitive areas" defined as institutions serving children, the elderly, and the medically compromised. Again, monitoring and enforcement are not reliably determined in many instances.

At the local level, numerous municipalities in the U.S.[259] and other countries[260] have policies to restrict cell towers on school property and many communities have removed wireless antennas from school properties. For example, the Supreme Court of India upheld a decision by the High Court of the State of Rajasthan to remove installations on school properties and playgrounds.[261]

Several countries focus their RFR monitoring and oversight on children's areas. Brazilian Law nr 11,934 includes regulations[262] defining a critical area as the 50-meters-radius around hospitals, clinics, schools, day care centers, and facilities for the elderly. The RFR levels must be assessed within 60 days after the issuance of a license and then regularly re-evaluated. Like France, Brazil hosts an online map[263] with the country's RFR measurements. Greece's National Observatory of Electromagnetic Fields[264] has 500 sensors providing RFR level monitoring for schools and other sensitive areas. Further measures that are commonly implemented internationally are listed in Table 3.

Regulatory gaps in the U.S

At the federal level in the U.S., policy changes are needed to address numerous regulatory gaps regarding

TABLE 3. International policy to Increase transparency, ensure compliance and reduce cell phone and RF radiation.

Policy	Country examples
Public RFR exposure limits are more stringent than ICNIRP/FCC limits	Italy, India, Israel, Croatia, Ukraine, Greece, China, Russia, Canada, Switzerland, Belgium, Bosnia Herzegovina, Grand Duchy of Luxembourg, Belarus, Georgia, Serbia, Slovenia, Montenegro, Bulgaria, Turkey, Liechtenstein, Tajikistan, Kazakhstan, Uzbekistan, Kyrgyzstan, Moldova, Kuwait, Republic of Moldova, Iraq
RFR monitoring program for cell tower/base station emission compliance and/or environmental RFR exposures.	France, Greece, Turkey, Spain, Romania, Serbia, India, Israel, French Polynesia, Croatia, Bulgaria, Tunisia, Malta, Brazil, Bahrain, Monaco, Bhutan, Senegal, United Kingdom, Australia, Spain, Austria, India, Israel, Gibraltar, Brussels Belgium, Switzerland, Norway, Lithuania.
Straightforward official government advice that the public and/or children "should" minimize cell phone RF exposure.	United Kingdom, Russia, Switzerland, Finland, Ireland, Germany, Belgium, Greece, Israel, Turkey, Singapore, France, Denmark, India, Austria, Cyprus, Canada, Italy, French Polynesia - Maryland U.S. for Wi-Fi in Schools (CEHPAC), Korea, Sri Lanka, Croatia, Krakow Poland, European Parliament Resolution 1815
Ban on mobile phone advertising to children	France, Belgium, French Polynesia, Russia
Ban on sale of phones designed for young children	Belgium, France, French Polynesia
SAR labeling on device, packaging or by retailer at point of sale	France, Israel, India, Belgium, Russia, Korea
SAR levels for cell phone models are publicly posted on easily accessible government website	France, Korea, Austria, Senegal, Germany,
Market surveillance program for cell phone SAR compliance	France, Canada
Public awareness program, robust website and/or educational campaign to educate the public on how to minimize RFR exposures from cell phones	France, French Polynesia, Israel, Cyprus, Israel

all aspects of control, monitoring, measuring and remediating wireless radiation.

First, no federal agencies with health or environmental expertise have reviewed the totality of the science to ensure U.S. regulations are adequate. In 2021 the U.S. Circuit Court of Appeals for the District of Columbia issued a landmark ruling in the case of Environmental Health Trust et al. vs. the FCC[55] that challenged the FCC's decision not to update the human exposure limits for RFR emissions from cell phones, Wi-Fi, and cell tower networks. The Court found that the FCC did not provide evidence of properly examining scientific evidence on the record and had ignored studies indicating low level non-thermal exposures could cause harm, especially for children. The Court then ordered the FCC to provide a reasoned explanation regarding these issues:

- the impacts of wireless radiation on children;
- the health implications of long-term exposure to RF radiation;
- the ubiquity of wireless devices and the technological developments since the FCC last updated its guidelines;
- the cell phone radiation emission test methods that use heat measurements and allow a space between the phone and body; and
- the impacts of wireless radiation on the environment.

Another critical regulatory gap is that when considering cell tower network emissions, there is no U.S. agency with health or environmental expertise engaged in any funded activities regarding health effects.

Unlike other countries that are gathering data via countrywide monitoring programs, the U.S. has no active federal field measurement program for assessment, compliance, or enforcement regarding cell tower and base station antenna RF emissions. The last federal agency report on RFR measurements was compiled in 1986 by the EPA.[265] When companies apply to build a cell tower in the U.S. near a school or homes, there are no requirements for real world RFR measurements before and after the antenna facilities are built, nor any requirement for annual measurements. The computer simulations provided by the company do not always provide estimated RFR levels for all of the areas that will be impacted by the cell antenna installation, such as inside an apartment that shares a wall with a building mounted antenna, or inside the room of a school or home in direct line of sight of the main beam of an antenna. Such close proximity installations can result in increased RF exposure[35,266,267] and are associated with various EMF-related symptoms.[208,210]

Although several nations post online maps with the location of cell towers and wireless facilities alongside RFR measurements, U.S. federal agencies neither collect, nor provide this information to the public. For example, small cell wireless facilities (such as those on poles less than 50 feet tall such as street lamps) generally do not need to be registered with the FCC.

International marketing, compliance and transparency measures

Some countries have enacted a variety of regulations designed to minimize children's exposure, ensure compliance with cell phone regulations, and ensure that the public has access to RFR information as shown in Table 3. For example, since 2010 France has prohibited the sale of cell phones designed for children under 6 years, and banned advertising cell phones to children under 14 years. In 2015, their cell phone labeling requirements were strengthened. Advertising must clearly recommend how to reduce exposure to the head or companies can be fined. In 2019, a joint order of the French Health and Finance Agencies[268] ordered that the cell phone consumer information should include several specific ways to reduce RF exposure to the brain, minimizing frequency and duration of use. In addition, the cell phone information includes "Keep radio equipment away from the belly of pregnant women," and "away from the lower abdomen of adolescents."[269]

2020 regulations[270] now mandate that computers, tablets and other handheld wireless electronics (as well as refurbished products) held close to the body were subject to the same labeling regulations as cell phones. In 2022, the French General Directorate for Competition, Consumer Affairs and Fraud Prevention found numerous violations[271] of their labeling requirements for wireless devices and issued over 200 warnings.

In 2014, Belgium implemented two Royal Decrees[272] that prohibited the sale and advertising of cell phones designed for children under 7 years old.[273]

Premarket cell phone and wireless device RFR testing

Some countries such as France and Canada perform independent SAR measurements of cell phone models to ensure regulatory compliance. Both countries have found that some phone models exceed their regulatory limits, even when tested at the manufacturer's stated separation distance, i.e. 5 or 10 or 15 mm from the head or body.

So far, over 35 non-compliant phone models have been either withdrawn from the French market or had software updates to decrease the RFR. The French National Frequency Agency, ANFR, posts their independent SAR test measurements for hundreds of cell phones online.[274] The U.S. does not have an oversight program for cell phone RFR emission compliance.

Furthermore, all cell phones and Wi-Fi devices such as routers, speakers, and gaming consoles have fine print instructions in their manuals stating that the user should maintain a specified minimum distance between their body and the phone or device in order to ensure compliance with regulatory safety limits.

Schools and child care settings

France, Israel, and regions in Belgium have removed Wi-Fi from kindergarten classrooms and restricted exposures in elementary classrooms. See Table 4. For example, French law (2015)[275] stipulates that Wi-Fi be off as the default setting, so that it is only turned on if needed for a particular classroom activity. The Parliamentary Assembly of the Council of Europe (PACE) Resolution 1815[276] (2011) recommends that "for children in general, and particularly in schools and classrooms, give preference to wired Internet connections, and strictly regulate the use of mobile phones by school children on school premises."

TABLE 4. International examples of policy measures to reduce RFR exposures in schools and child care settings.

Recommendations to prefer wired over Wi-Fi in kindergartens and schools	France, Israel, Germany, French Polynesia, Salzburg Austria, Maryland U.S.
Wi-Fi banned in child care settings and kindergarten	France, Israel, Ghent Belgium, French Polynesia, Cyprus
Wi-Fi off or minimized in elementary	France, Israel, Cyprus, Various municipal school districts worldwide

In the U.S., there are no specific school-focused or workplace-based federal regulations for RFR exposures. The Maryland State Children's Environmental Health and Protection Advisory Council report on Wi-Fi in school[277] recommends the reduction of RFR exposures in schools "as much as feasibly practical." Clegg et al.[278] outlines how to minimize RFR in buildings and includes the Collaborative for High Performance Schools[279] criteria to reduce RFR and ELF EMF in classrooms. (See a summary of recommendations below.)

Recommendations by Maryland Expert Advisors to the Governor and the Collaborative For High Performance Schools include:

- Install and use wired local area network (LAN) for internet access instead of Wi-Fi and connect classroom tech with cables whenever possible and always when building/remodeling.
- Ensure devices (tablets and laptops) are always used on a desk, not lap.
- Laptops, tablets and notebooks should have an Ethernet port and a physical switch to disable all wireless radios at once.
- Cell phones should be powered off and stored away during the school day. Wireless wearables should be turned to airplane mode.
- Prohibit use of DECT and cordless phones.
- Corded telephones should be installed in every classroom and there should be a way that students can contact parents and make calls during the day for planning purposes.
- Schools should integrate education on why and how to reduce RFR exposure into elementary, middle and high school class curriculum.
- Cell towers and wireless facilities should not be built on or adjacent/near to school property.
- Measure ELF and RFR levels in classrooms and sports areas yearly and when new technology is added to classrooms.

Healthcare settings

Sources of non-ionizing EMF exposure inside hospitals and healthcare facilities come from both the wireless networks (RFR) as well as electrical medical equipment (ELF-EMF).

EMF levels in neonatal units have been the subject of research due to the elevated exposure to an especially vulnerable patient group. Measurements of ELF inside incubators can range from 2 to 100 mG, depending on the distance from the top of the mattress to the electrical equipment.[280] After documenting higher levels of low frequency EMF levels inside closed incubators as compared to the ambient levels in the room, Penn State Medical Center researchers moderated the exposure through a grounding technique and found the mitigation improved infant's vagal tone, a marker of vulnerability to stress, and the risk of developing necrotizing enterocolitis.[281]

RFR in neonatal intensive care units primarily originates from staff and families' use of cell phones and wireless devices. A prudent avoidance strategy is recommended because these newborns are particularly vulnerable.[282]

In 2017, in Israel measurements of magnetic field EMF were taken for incubators in neonatal units at the request of the Ministry of Health and the Ministry of Environmental Protection[283] and they found a range from 0.05 to 5 μT. The Israel Ministry of Environmental Protection identified manufacturer approved efficient shielding methods to mitigate exposure in incubators and recommends reducing the duration of exposure as much as possible and prioritizing the use of low EMF incubators.

In Cyprus, the National Committee on Environment and Children's Health, under the auspices of the Ministry of Health, worked with the Archbishop Makarios III Hospital to pilot an RFR reduction program[284] in the pediatric intensive therapy unit and neonatal units. They removed the Wi-Fi access points, installed wired LAN networks and launched a multimedia educational program for families. RFR levels were measured before and after the mitigation and the measures resulted in a significant reduction in ambient exposure in the units.

The Agaplesion Diakonie Hospital in Hamburg, Germany has designed two "environmental" rooms for people with multiple chemical sensitivities and/or environmental allergies including sensitivity to electromagnetic fields. In addition to using low VOC emission building materials and fragrance free cleaning, several measures have been taken to reduce exposure to non-ionizing electromagnetic fields including the installation of power circuit breakers and prohibition of the use of cell phones.[285]

Recommendations for healthcare settings to minimize exposures, to support positive health outcomes as well as to accommodate patients with sensitivities:[13,83,197,199,215,275,281]

- Decrease RFR exposures in pediatric healthcare settings including waiting rooms, treatment areas, hospital rooms, and administrative workspaces by prioritizing wired connections and setting routers to their lowest operating settings;
- Ensure facilities have spaces with adequate EMF mitigation for treatment of sensitive patients;
- Educate patients, families, and staff;
- Utilize medical devices, equipment and technology designed without wireless features, or configured such that wireless connections are not essential and can be turned off when not in use; and
- Work with companies on research and design of safer technologies.

Conclusion: next steps for clinicians to better protect the young from impacts of RFR

Modern telecommunications have been embraced for their innumerable benefits to society, but we have been slower to acknowledge the need to avoid and reduce harms to youngsters or to the natural world on which our lives depend.[286] Fortunately, alternatives to employing wireless devices can provide safer, faster and more efficient technical performance for many modern applications. There are many distinct physical, psychological and sociological grounds for moderating children's screen time to promote healthy development. The principle of ALARA—as low as reasonably achievable—ought to be adopted as a strategy for RFR health and safety protection.

While such measures are being implemented in clinicians' offices, clinics and the like, there is a critical need for an independently funded training, research and monitoring program to identify major data gaps in the field which are substantial, to set relative priorities for research and training, and to conduct long term studies of the physical and psychological impacts of rapidly changing technological milieu, including ways to mitigate impacts through modifications in hardware and software.

The medical community has a critical role to play in the prevention and treatment of EMF associated illness. Steps that doctors and other healthcare professionals can take include:

- Federal level: Advocate with the AAP and other health professionals for a reassessment of RFR exposure limits and the development of standards that adequately address biological impacts, children's vulnerabilities and current use patterns.
- State level: Engage membership with educational and training activities as well as resolutions to support federal initiatives.
- Support policies that reduce EMF exposure for children in home, child care, school, health care, and recreational settings.
- Support the continued development of clinical guidelines for prevention, treatment and diagnosis of EMF related illness.

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