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Wi-Fi technology and human health impact: a brief review of current knowledge

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An enormous increase in the application of wireless communication in recent decades has intensified research into consequent increase in human exposure to electromagnetic (EM) radiofrequency (RF) radiation fields and potential health effects, especially in school children and teenagers, and this paper gives a snap overview of current findings and recommendations of international expert bodies, with the emphasis on exposure from Wi-Fi technology indoor devices. Our analysis includes over 100 *in vitro*, animal, epidemiological, and exposure assessment studies (of which 37 *in vivo* and 30 covering Wi-Fi technologies). Only a small portion of published research papers refers to the "real" health impact of Wi-Fi technologies on children, because they are simply not available. Results from animal studies are rarely fully transferable to humans. As highly controlled laboratory exposure experiments do not reflect real physical interaction between RF radiation fields with biological tissue, dosimetry methods, protocols, and instrumentation need constant improvement. Several studies repeatedly confirmed thermal effect of RF field interaction with human tissue, but non-thermal effects remain dubious and unconfirmed.

KEY WORDS: exposure to RF fields; e-school; radiofrequency; SAR

Recent decades have seen an enormous increase in the application of wireless communication, with consequent increase in human exposure to electromagnetic (EM) radiofrequency (RF) radiation fields (1–3). Before that, the most common sources of RF radiation had been radio and TV broadcast antennas. Wi-Fi-based technology and receivers, such as laptops, tablets, cordless, and mobile phones with their base stations, and Bluetooth devices have now been available on the global market for 15–25 years. Today, there is virtually no laptop computer, smartphone, tablet, or communication gadget not equipped with Wi-Fi technology, which is a trademark name for wireless networking products certified by the Wi-Fi Alliance to be compliant with the Institute of Electrical and Electronics Engineers' (IEEE) 802.11 family of standards (4, 5). Wi-Fi is also increasingly used in public transport, vehicles of all types, aviation, household devices such as audio equipment, thermostats or alarm systems, smart utility meters and detectors, and gaming gadgets, and in industrial and security settings. Yet vast majority of the research about potential adverse health effects of the microwave part of the RF frequency spectrum (300 MHz to 300 GHz) has been focused on mobile phone devices, since they emit more RF radiation than other common RF communication devices (6). Modern pocket-size gadgets have widely been made available to the public by telecom operators to secure global Wi-Fi hotspots and enormous communication opportunities. For example, Wi-Fi signals in a sample of schools in Belgium and Greece have been reported to contribute with 6–13 % to total electric field strength originating from various RF field sources (Figure 1) (7). Jordan has a highly developed telecommunication infrastructure to cover the refugee camps with Wi-Fi signal (8), support learning in schools, and cover municipalities offering public safety network as the country's major civilisation priority. Researchers in Spain performed the measurements and analysis of personal exposures outdoors and indoors of Spanish schools (9). Preliminary findings of an ongoing study of possible health effects of new telecommunication technologies in Croatian schools (10) indicate that Wi-Fi contributes with 6–8 % to total EM RF radiation exposure burden during classes using Wi-Fi technology, but they do not include remote classes using wireless technologies.

Wireless standard

The specific way of utilising RF fields in mobile telecommunication is referred to as "wireless standard", named after each generation of mobile telecommunications replacing each other over the last 30 years: 1G, 2G, 3G, 4G, and 5G (11), with 6G already announced (12). Each generation consists of a family of different wireless protocols (for example, LTE is a well-known protocol in the 4G family of protocols).

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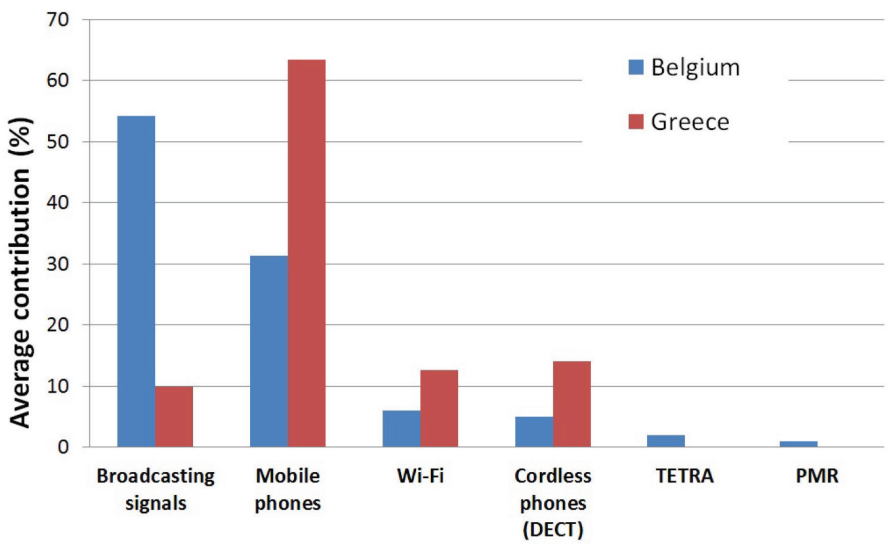

Figure 1 Average contribution (%) of various RF signals measured as electric field strength (V/m) in Belgian and Greek schools (7)

Broadcasting and classic telecommunication RF field signals include frequency modulation (FM), digital audio broadcasting (DAB), and television signals. Mobile phone signals (2G, 3G, and 4G) include protocols pertaining to the Global System for Mobile Communications at 900 MHz and 1800 MHz (aka GSM 900 and 1800) and the Universal Mobile Telecommunications System (aka UMTS). The Wi-Fi protocol is based on the IEEE 802.11 family of standards. The Digital Enhanced Cordless Telecommunications (DECT), the Terrestrial Trunked Radio (TETRA), and Personal Mobile Radio (PMR) protocols are part of the 2G/3G family of standards.

Interaction mechanism of RF fields with tissue

RF fields do not ionise cell genome or damage cells and tissues in any direct way, but research indicates that they affect living organisms via thermal effects (tissue heating) and non-thermal effects such as vibration and rotation of molecules (especially those that have an asymmetric charge or that are polar in structure), oxidative stress, genetic damage, or altered cell membrane permeability (13).

An RF field in air can be reflected, transmitted, refracted, or scattered by a biological body. Reflected and scattered fields may proceed in directions different from that of the incident RF field, while transmitted and refracted fields interact with biological body tissues in selective ways. These interactions strongly depend on the frequency, waveform, and strength of the induced fields and energy deposited or absorbed by a biological system as a whole. In addition, the distribution of the fields inside a biological system such as the human body is affected by the distance and location of the RF source with respect to the body, its anatomy, posture, and the surrounding environment. Another general characteristic of an RF field is that the higher the frequency, the lower the depth of its penetration into the body. The electric field component of an EM wave penetrating tissue drops to 37 % of its initial value at the distance known as the skin depth (14, 15). Skin depth of each tissue type or organ depends on their electrical permittivity and conductivity. The general expression for skin depth γ for poor (non-metal) conductors such as dry skin, at high frequencies is as follows (14):

$$\delta = \frac{1}{\omega}\left\{\left(\frac{\mu\varepsilon}{2}\right)\left[\left(1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2\right)^{\frac{1}{2}}-1\right]\right\}^{-\frac{1}{2}} \quad /1/$$

where ω is the angular frequency, and ε, σ, and μ are skin permittivity (F/m), conductivity (S/m), and magnetic permeability, respectively. In biological materials, μ in tissues has essentially the same value as that of free space, $4\pi\times10^{-7}$ H/m. Skin depths of tissues with low water content such as fat and bone are greater than those with higher water content such as muscle and skin. The relationship between skin depth of EM RF waves and frequency is shown in Figure 2.

Table 1 provides typical skin depths for tissues with low and high water content at selected exposure frequencies (16, 17).

Common telecommunication frequencies of the 2G, 3G, 4G, and even 5G wireless standards can penetrate tissues a couple of centimetres (14, 18). When absorbed, they release their EM energy to the tissue, which adds to the energy being produced by body metabolism (19). Human body can adjust to small temperature increases caused by RF field interaction with tissue in the same way as it does when we exercise or do sports, because our body can regulate its internal temperature.

Thermal effects of EM field interaction with tissue (14, 15, 19) can occur within the range of a near EM field, that is, at distances from the emitting antennas which are shorter than the so called Frauenhofer distance (14). In case of mobile phones and Wi-Fi as

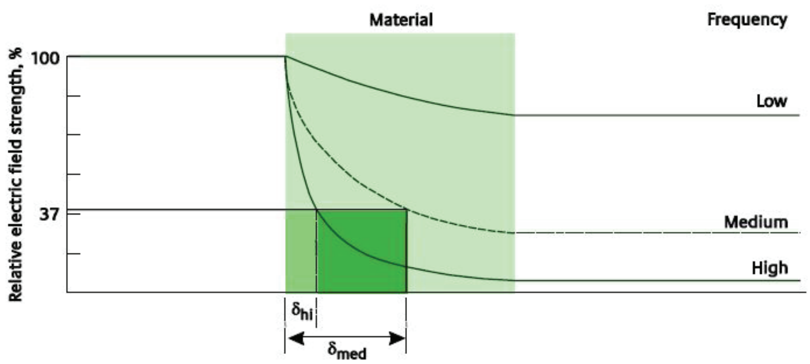

Figure 2 How EM RF energy is absorbed by biological materials, i.e. how skin depth decreases with higher frequency. Reflection of the incident radiation is assumed negligible at each interface in this diagram. Skin depth at high frequency, δ_{hi}, is less than that at medium frequency, δ_{med}. (14, 16)

transmitting sources, this distance is less than 35 cm (depending on the frequency of an RF source). With a 2.45 GHz Wi-Fi source it is up to 16 cm around the Wi-Fi antenna, and with a 5 GHz source up to 33 cm (17). Typical near-field effects are negligible if the distance from the antenna is greater than a few wavelengths. If the RF field interacts with a tissue outside the Frauenhofer radiation zone or the tissue is in the far RF field (relatively uniform wave pattern and wave length smaller than far field distance and larger physical linear dimension of the antenna smaller than far field distance) (14), thermal effects are not expected, but a certain kind of stochastic non-thermal effects can occur in tissue.

While the thermal effects of RF radiation fields are well acknowledged and extensively studied, there is a significant dispute among scientists and in general public about the nature and behaviour of non-thermal effects (19-22).

In 1998, the International Committee on Non Ionizing Radiation Protection (ICNIRP) issued a report (23), updated in 2020 (24), that provides basic restrictions and reference levels for workers and general population (Table 2) based on health effects observed in experimental animals due to a rise in body temperature of more than 1 °C (including altered neural and neuromuscular functions, increased blood-brain barrier permeability, lens opacities, corneal abnormalities, stress-associated changes in the immune system, haematological changes, reproductive changes, teratogenicity, and changes in cell morphology, water and electrolyte content, and membrane function). This increase corresponds to whole-body exposure to specific energy absorption rate (SAR) of approximately 4 W/kg for about 30 min (23, 24). In case of partial body exposure, this temperature rise is expected at SAR values of 100–140 W/kg, based on cataract findings in rabbits (25). Both whole and partial body SAR values are corrected by a safety factor of 10 for workers and 50 for general population (23, 24). Both take into account possible variations in ambient temperature, humidity, level of physical activity, age, and health status (18, 24).

Regarding thermal (primarily genotoxic and carcinogenic) and non-thermal effects, the 2009 ICNIRP statement on EMF Safety Guidelines says that "the scientific literature published since the 1998 guidelines has provided no evidence of any adverse effects below the basic restrictions and does not necessitate an immediate revision of its guidance on limiting exposure to high frequency electromagnetic fields" (26). Furthermore, reviews conducted by the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) (27), the Health Council of the Netherlands (28), and the Swedish Radiation Safety Authority (29, 30) conclude that there is currently no evidence and no consensus that RF EMFs are carcinogenic.

In 2020, the updated ICNIRP RF EMF Guidelines for Limiting Exposure to EM fields (100 kHz to 300 GHz) (24) replaced and superseded those issued in 1998 (23), but questions remain, especially those regarding epidemiological evidence of RF radiation-related carcinogenesis and potential mechanisms of non-thermal effects. According to the new guidelines (24), all SAR values are to be averaged over six minutes, and localised averaging mass should be 10 g of contiguous tissue. Maximum SAR so obtained should be used to estimate exposure (13).

In order to limit or avoid auditory effects caused by thermoelastic expansion, for pulsed exposures in the frequency range of 0.3–10 GHz and for localised exposure of the head, ICNIRP (24) recommends an additional restriction: specific energy absorption (SA) should not exceed 10 mJ/kg for workers and 2 mJ/kg for the general public, averaged over 10 g tissue.

The aim of this review is to sum up current information about recognised health risks of RF radiation emitted from Wi-Fi sources to general public, with a focus on children and teachers exposed to Wi-Fi EMF in schools. We also wanted to identify issues that need further research.

Foster and Moulder (31) nicely summarise the main concern regarding exposure of children to RF fields: "a person who spends hours a day glued to a smartphone or tablet may well experience all sorts of neurocognitive effects – from the use of the technology, not from RF exposure. EEG studies may well be useful to identify and clarify any such effects. And meanwhile, readers are reminded to closely monitor what their children are doing as they surf the Internet with their Wi-Fi-enabled computers and smartphones."

Table 1 Conductivity and skin depth of low and high water content tissues at selected EM RF

Frequency	Tissues with low water content				Tissues with high water content			
	Fat		Bone		Muscle		Skin	
	σ (S/m)	δ (mm)	σ (S/m)	δ (mm)	σ (S/m)	δ (mm)	σ (S/m)	δ (mm)
150 MHz	0.04	366.1	0.07	301.0	0.7	67.2	0.5	85.0
450MHz	0.04	301.9	0.10	202.2	0.8	51.3	0.7	52.9
835 MHz	0.05	252.0	0.14	139.5	0.9	43.5	0.8	41.5
1.8 GHz	0.08	157.1	0.28	66.7	1.3	29.2	1.2	28.3
2.54 GHz	0.10	117.1	0.39	45.8	1.7	22.3	1.5	22.6
3 GHz	0,13	93.6	0.51	35.2	2.1	18.0	1.7	18.9
5 GHz	0.24	49.4	0.96	17.7	4.0	9.3	3.1	10.5
10 GHz	0.58	19.6	2.13	7.3	10.6	3.3	8.0	3.8

Skin depth is calculated based on permittivity and conductivity of tissues taken from Gabriel at al. (15, 16) and the formula used for calculation is taken from (16, 17)

OVERVIEW OF CURRENT RESEARCH

We collected information from two extensive reviews of human exposure and health effects of radiofrequency (RF) fields by Verschaeve in 2012 (1) and Foster and Moulder in March 2013 (5), from peer-reviewed articles in English indexed in the Web of Science and IEEE ICES databases and published since March 2013, and from expert reports published since 2011 (9, 12, 20, 22, 28-32).

Expert group reports on biological effects of RF radiation

Verschaeve (1) made an overview and evaluated 34 reports issued by (inter)national expert groups between 2009 and 2011 (1). All but one (33) concluded that there was no clear indication of adverse health effects from RF exposure from wireless communication technology. One group, the Council of Europe's Committee on the Environment, Agriculture and Local and Regional Affairs, recommended several measures to limit population exposure to RF radiation. However, its conclusions are not evidence-based but follow the precautionary principle.

The International Agency for Research on Cancer (IARC) in its Monographs (34) concluded that there is limited evidence for the carcinogenicity of RF fields in animals and humans, the latter being based on positive associations observed between the use of mobile phones and glioma and, to a lesser extent, acoustic neuroma. RF fields have therefore been classified as possibly carcinogenic to humans (Group 2B) who use mobile phones extensively. Comparing different sources of RF radiation, IARC has also concluded that "the general population receives the highest exposure from transmitters close to the body, including hand-held devices such as mobile telephones". Exposure from other sources, such as mobile-phone base stations and TV and radio stations is typically several orders of magnitude lower, and from Bluetooth wireless hand-free kits around 100 times lower than that of mobile phones (34).

Following the precautionary principle, the Belgian Superior Health Council report from 2009 (35) recommended more severe exposure limits (3 V/m at 900 MHz for mobile phones) due to scientific uncertainties (1).

Only the Bio-Initiative group report (33) considered that there was sufficient evidence to warn against hazardous properties of RF radiation for humans for almost all biological endpoints investigated (brain tumours and acoustic neuromas, neurodegenerative diseases, childhood leukaemia, and breast cancer in men and women) even at low, everyday life exposure levels, and that existing public exposure standards are inadequate. Verschaeve (1) points out a number of deficiencies of this report: possible conflicts of interest were not assessed, the group did not reach a consensus, as the report consists of a number of chapters written by individual authors, apparently without consultation or discussion between them, the methods used to collect literature data and selection criteria were not defined, which resulted in bias toward studies with positive findings. Uncertainties remain, especially regarding adverse effects in adults (primarily head and neck tumours) following long-term exposure (well beyond ten years) and in children, since information for this age group is limited.

Regarding non-carcinogenic outcomes, studies are inconsistent, and some point to the potential role of the nocebo effect (an adverse non-specific effect that is caused by expectation or belief that something is harmful) (36, 37).

Most of the reports included in Verschaeve's (1) review have been updated over the past seven years. In 2012, the European Health Risk Assessment Network on Electromagnetic Fields Exposure (EFHRAN) issued an updated report (38) that was consistent with IARC (34) conclusion on possible carcinogenicity of RF fields regarding brain tumours (Group 2B). For other evaluated health endpoints (other types of tumours, neurodegenerative diseases, reproduction, cardiovascular diseases, and non-specific symptoms affecting well-being) the conclusion remained the same as in the previous report: for none of them was there sufficient evidence for a causal association with RF fields.

Also, in 2012, British Health Protection Agency (HPA) issued an extensive report (32) on *in vitro*, *in vivo*, and human studies of RF field exposure health effects. It concluded that *in vitro* and *in vivo* evidence of carcinogenicity and changes in neurology, behaviour, gene expression, and permeability of the blood-brain barrier was inconsistent at exposure levels below guideline levels, and so were neurophysiological studies in humans, including children. Studies in children were too scarce and too small in sample sizes to provide any strong evidence. Regarding non-specific symptoms (39), the Agency's expert group found no evidence of causality for short-term exposure, whereas evidence for long-term exposure was of insufficient quality to draw any conclusion. Even though evidence of RF field effects on sperm quality was found weak in the report, some positive results were found to justify further research. Other reproductive evidence was found to be too limited to allow any conclusion. Regarding cardiovascular effects in humans, what limited number of studies was carried out showed no substantial evidence of adverse effects, and cancer studies in humans were also too weak to either prove or disprove the causality, especially in children.

In May 2015, ICNIRP released a report in which it re-examined the guideline values for the thermal effect and updated information on heat-related effects and thresholds of thermal damage caused by RF exposure in the 100 kHz to 300 GHz frequency range (40). The expert group concluded that the six-minute averaging time used in international guidelines was valid for whole-body exposure but with large uncertainty, and proposed 30 minutes as a more appropriate averaging time for localised exposure and less than one minute for implanted medical devices. Further research of RF thermal effects was recommended, especially in view of individual variations in temperature sensitivity in persons at particular risk and between different body tissues. The ICNIRP note on Recent Animal Carcinogenesis Studies (41), published in 2019, evaluated the results of three large animal studies (42-44) that investigated carcinogenicity due to long-term exposure to RF fields generated by mobile phones and base stations. Although all three studies reported significantly higher incidence of carcinogenic outcomes in male rats, the ICNIRP concluded that their results were not consistent with each other or the literature and that methodological limitations preclude drawing conclusions about carcinogenicity due to RF EMF exposure (41).

Also in 2015, SCENIHR (27) confirmed conclusions from its previous report (45), having maintained the opinion that epidemiological studies had not shown increased risk of brain tumours, other head and neck cancers, or of other malignant diseases in mobile phone users, including children. Furthermore, the SCEHNIR expert group found unclear the relevance of small electroencephalogram (EEG) changes indicating that RF exposure may affect brain activities in humans and the proposed mechanistic explanation lacking. The group also confirmed the lack of evidence that mobile phones affect cognitive function in humans. SCENIHR's review of available research data did not establish adverse effects on reproduction and development, but it did point out conflicting results and methodological limitations of studies on child development and behavioural problems as well as poor quality of studies on male fertility. Regarding the symptoms of the "idiopathic environmental intolerance attributed to electromagnetic fields" (IEI-EMF) syndrome, the expert group concluded that recent research confirmed previous conclusion that there is no causal relationship. In order to help improve data quality in further research of RF-related health effects, SCENIHR developed a set of recommendations and methodological guidelines for experimental design and minimum requirements to ensure their usability in risk assessment.

Still in 2015, the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) (46) confirmed its conclusion from 2009 and issued the following statement: "There is no established scientific evidence that the low exposure to RF EME [electromagnetic environment] from Wi-Fi adversely affects the health of children or the general population". It, therefore, does not advise against the use of Wi-Fi in schools and other places.

In 2016, the Institution of Engineering and Technology (IET) issued a position statement (36) that also confirmed conclusions from previous reports and stated that the balance of scientific evidence in humans and animals did not indicate adverse health effects at low-level RF exposure. However, the expert group warned that experimental replication studies failed to confirm previous results (under the same conditions) and that many replications were biased toward publishing only positive findings of adverse effects, even though they did not rely on robust methodology. The group, therefore, invited researchers and journals to publish all findings from well-designed, robust studies.

To conclude, the updated reports do not differ much from their previous releases. Possible (Group 2B) brain carcinogenicity of RF near-field radiation due to heavy use of mobile phones is neither up- or down-classified, since no new high-quality data have been produced, because long-term exposure (10–15 years) is yet to be evaluated by longitudinal studies such as COSMOS, an epidemiological study launched in March 2010 (47-49) and the Generalised EMF Research using Novel Methods project (GERoNiMO) (50), which includes both human and animal studies and focuses not only on RF radiation-related risk of cancer but also

Table 2 Basic restrictions for time-varying electric and magnetic fields for frequencies 10 MHz–10 GHz according to the International Commission on Non-Ionizing Radiation Protection (24)

	Whole-body average SAR (W/kg)	Localised SAR (W/kg)	
		Head and trunk	Limbs
Occupational exposure	0.4	10	20
General public exposure	0.08	2	4

on neurodegenerative diseases, behaviour, reproductive outcomes, and aging. The results of these projects are still under consideration, replication, and professional review of dosimetry methodology used.

Regarding non-carcinogenic adverse effects in humans, no updates have shown sufficient evidence to either prove or disprove a causal association with RF radiation, but certain indications of biological effects in humans have been reported, such as an effect on EEG activity but without clear relevance or mechanistic explanation. The same goes for limited evidence of RF effects on sperm quality, which calls for further research, as do studies in children, which are sparse and have small sample sizes to draw any informed conclusion. In this age group further research is particularly encouraged in terms of carcinogenicity and developmental and behavioural problems. The ongoing studies of non-carcinogenic effects include the GERoNiMO project mentioned above and the Study of Cognition, Adolescents and Mobile Phones (49), for which baseline and first follow-up data collection was completed in July 2015 and July 2018, respectively. This type of project should be broadened to cover large adolescent population groups who are dependent of wireless communication technology in social interactions.

Although the above mentioned reports refer to non-thermal RF exposure from mobile phones and other wireless communication devices (including Wi-Fi), they are primarily focused on exposure to mobile phones, which in terms of output power is markedly higher than RF exposure from other Wi-Fi sources (see below).

ASSESSMENT OF EXPOSURE TO RF EMF EMITTED BY WI-FI EQUIPMENT AND POSSIBLE RELATED HEALTH EFFECTS

Exposure assessment

Wi-Fi devices contain low-powered RF transceivers. In the European Union the peak output power of Wi-Fi transmitters (based on the IEEE 802.11 family of standards) is limited to 0.1 W for Wi-Fi devices operating in the 2.45 GHz band - the 2006 EN 300 328 standard (51) and 0.2 or 1 W for devices in the 5.2 and 5.5 GHz bands, respectively - the 2007 EN 301 893 standard (52). RF exposure from these devices, both from access points located in a house or public building and from clients (e.g. laptops) is far below the adopted international limits. Compared to the ICNIRP reference value of 10 W/m^2 (i.e. 10,000 mW/m^2) for frequencies between 2 and 300 GHz recommended for whole-body exposure of the general population (24), calculated peak power density is about 330 mW/m^2 at the distance of 20 cm and 13 mW/m^2 at the distance of 1 m for a typical Wi-Fi device operating at an output power of 0.1 W (20). In reality, most Wi-Fi transmitters operate at considerably lower power. In addition, since data packages are not transmitted through wireless local area network (WLAN) continuously but in pulses with a median duty cycle (the ratio of active duration to total duration of the transmission signal) of 1.4 % (10.4 % in the 95th percentile) measured in different general and industrial environments, EM fields happen to be overestimated by a factor of 8 (53). These data are in line with the experiment conducted by Peyman et al. (19) in which EM field strengths typical for UK schools ranged from 5 to 17 mW in the 2.4 GHz band and from 1 to 16 mW in the 5 GHz band for laptops, and from 3 to 28 mW at 2.4 GHz and from 3 to 29 mW at 5 GHz for access points. For Wi-Fi devices operating at 2.45 GHz, maximum power density at the 50 cm distance was 22 mW/m^2 for laptops and 87 mW/m^2 for access points, while at the 1 m distance these values dropped to 4 mW/m^2 and 18 mW/m^2, respectively. Peyman et al. (19) also noted that radiation from laptops was minimal toward the user's torso, and maximal across the vertical planes bisecting the screen and the keyboard (affecting the operators' palms and fingers). In another study by the same group of authors the duty cycles of laptops used by UK schoolchildren ranged from 0.02 % to 0.91 %, and those of access points from 1 % to 11.7 %. A similar study conducted in 23 Australian schools reported a median duty cycle of 6.3 % for 2.45 GHz and 2.4 % for 5 GHz transmissions (54). In a 10-year-old schoolchild model (55) the authors predicted the maximum time-averaged power density from a laptop at the 50 cm distance to be 0.22 mW/m^2, with the peak localised SAR of 0.08 mW/kg in the torso region at 34 cm from the antenna. Table 3 shows RF EMF measurements in indoor school environments from various countries in Europe, Australia, and New Zealand. All reported values are well, often several orders of magnitude, below the ICNIRP reference values.

Not even cumulative exposure with many users in a room accessing WLAN at the same time is not expected to pose a health risk. According to the calculations of Khalid et al. (55), even in the unlikely event that 30 laptops in a classroom transmit at the maximum power density of 0.22 mW/m^2 at the 0.5 m distance (with the maximal, 1 % duty cycle) at the same time, the time-averaged exposure from all laptops would be only 6.6 mW/m^2. Karipidis et al. (54) also showed no increase in personal exposure to Wi-Fi in classrooms with many students and access points. Instead, exposure was rather determined by the closest exposure source (access point or client device).

Comparing urban environmental RF exposure from different sources in five European countries (Belgium, Switzerland, Slovenia, Hungary, and the Netherlands), Joseph et al. (56) found that the highest time-averaged exposure for bystanders (exposure of users was not measured) was related to mobile phone handsets (including cordless phones), while Wi-Fi contributed with only 2–12 % in homes and <1–8 % in offices. Very similar results were reported by Lahham et al. (57) in indoor home and public environments in the city of Hebron. The highest total power density of around 0.02 W/m^2, found at any of the 343 measured locations was well below the ICNIRP limit for the general public of 10 W/m^2, whereas the relative contribution from WLAN was 9 %. In another study (58) that assessed far-field RF exposure in kindergarten children in

Melbourne, Wi-Fi access points (routers) contributed with an insignificant portion to the overall exposure compared to other RF sources, especially mobile phone base stations. In Australian schoolchildren exposure to Wi-Fi RF was also reported very low and comparable or lower than from other sources in the environment (54). The prevalence of exposure to mobile phones (including DECT) was also evidenced in ten Belgian and five Greek schools, in which their cumulative electric field strength was about six times higher compared to Wi-Fi devices (7). In real-life estimations which consider the frequency of operation, the maximum time-averaged output power of GSM mobile phones, which apply Time Division Multiple Access (TDMA), is 125 or 250 mW, depending on whether they operate at 900 MHz or 1,800 MHz, respectively (19). The maximum power of 125 mW is also reported for 3G phones. According to data presented above (19), the maximum output power of access points is roughly four to nine times lower than that of mobile phones. Moreover, the antennas of Wi-Fi devices are usually further away from the body during normal use than those of mobile phones.

However, we still do not know much about the level of exposure in persons who use mobile phone data traffic through WLAN for voice (or video) calls (e.g. via Viber or WhatsApp) without a headset or mobile internet connection.

Health effects

In their systematic review of biological effects of Wi-Fi exposure that included scientific literature published by March 2013, Foster and Moulder (5) identified only seven peer-reviewed articles with well-defined exposure systems and dosimetry (59–66) and six non-peer-reviewed articles lacking these data (67–72). The authors found no statistically significant response to Wi-Fi for any of the endpoints studied in the first seven studies, namely fertility and development (including the immune system and the brain) and stress markers in an animal model, whereas the other six, non-peer-reviewed studies reported EEG changes in humans, sperm changes and oxidative stress in rat testes, and altered gene expression, but these findings, warned the authors, should be taken with reserve, as they lack in scientific rigour (unblinded or no sham-exposed control in addition to technical deficiencies mentioned above).

Brain effects in humans

Regarding EEG changes observed in human volunteers (68, 72), Foster and Moulder (5) point out that effects of low-level RF exposure (excluding Wi-Fi) on brain activity are small and difficult to confirm. The 2013 report issued by the British Columbia Centre for Disease Control (BCCDC) (32) confirms that available literature shows no or inconsistent effects of mobile phones on neurobehavioral parameters and brain physiology. It is still unclear which mechanisms may be responsible for RF effects on brain function (28, 29, 32), but some propose interference of pulsed RF signals with brain electric oscillatory activity and changes in cell signalling (73). Repetitive studies claim there is no evidence that RF affects the cognitive function in humans.

Recently published findings on Wi-Fi exposure and brain functioning seem to follow the pattern observed for mobile phone exposure. Papageorgiou et al. (68, 72) reported sex-dependent EEG

Table 3 Examples of Wi-Fi exposure in school indoor/classroom environment

Reference	Country / Sample	Source / Distance from source (m) (Number of measurements)	Electric field strength (V m^{-1})	Power density (W m^{-2})	SAR (W/kg) localised (head and trunk)
Khalid et al. 2011 (55) Peyman et al. 2011 (19)	United Kingdom / 3 primary, 3 secondary schools	access points*/ 0.5	5.7[b]	-	
		laptops / 0.5	2.9[b]	-	0.00008[c]
Joseph et al. 2010 (56)	Hungary / 31 primary school teacher[d]	Wi-Fi devices*	2-5	-	-
Vermeeren et al. 2013 (7)	Belgium / 10 schools	various Wi-Fi devices*#	0.05[a], 0.24[b]	-	-
	Greece / 5 schools		0.09[a], 0.20[b]	-	-
Verloock et al. 2014 (111)	Belgium / 5 primary and secondary schools	access points various Wi-Fi clients*#	0.34[a], 2.52[b]	-	-
Gledhill 2014 (59)	New Zealand / 2 schools	access points# / 2 laptops / <0.5	-	0.0025[a], 0.02[b] 0.002[a], 0.03[b]	-
Karipidis et al. 2017 (54)	Australia / 7 primary 16 secondary schools	access points*# / 1.9	-	0.0004[a], 0.04[b]	-
Prlić et al. 2021 (10) & Yet unpublished data	Croatia /151 primary & secondary schools	access points*# /across the whole classroom (grid 1m x 1m)	< 0.66 [b]	-	0.029*[f] 0.0088 #[f]
Relevant ICNIRP reference levels[$]			**61**	**10**	**2**

SAR - specific energy absorption rate. * 2.4–2.5 GHz; [#]5.15–5.85 GHz; [a] average value; [b] maximum value; [c] peak localised SAR in the torso region in a 10-year-old child model at 34 cm from the antenna; [d] personal dosimetry; [f] localised averaged value for any 10 g of tissue (based on simulation for total tissue mass of 125.39 kg)[;] [$] reference levels for general public exposure to time-varying electric and magnetic fields: electric field strength and equivalent plane wave power density refer to the 2–300 GHz frequency range, while SAR values refer to the 10 MHz–10 GHz frequency range changes in volunteers exposed to 2.4 GHz Wi-Fi at 1.5 m distance from the head while performing the Hayling Sentence Completion task: women showed higher P300 wave amplitudes than men (believed to reflect attention and working memory operations of the brain).

Zentai et al. (74), in contrast, found no effects on EEG or attention in participants exposed to 2.4 GHz Wi-Fi at 40-cm distance for 60 min, even at the highest, 1 W output power and 100 % duty cycle.

Brain effects in animals

Deshmukh et al. (75) described diminished cognitive function and higher levels of heat shock protein 70 and DNA damage in rat brain following exposure to the 2.45 GHz far field at the SAR of 0.67 mW/kg for 2 h a day over 180 days. In mice exposed to RF at the SAR of 14.6 mW/kg, Shahin et al. (76) found increased oxidative/nitrosative stress and enhanced apoptosis in the hippocampal region as well as learning and spatial memory deficit that correlated with exposure duration (15, 30, and 60 days). In contrast, Banaceur et al. (77) found no adverse effects in adult male transgenic mice prone to develop Alzheimer's-like cognitive impairment after one month of exposure to Wi-Fi, even though the SAR applied was high (1.6 W/kg). In fact, they reported a beneficial effect against anxiety, but could not propose a mechanism that would explain it.

Effects on male fertility

The 2013 BCCDC report summary (32) on male fertility states that "to date, animal and human data are contradictory and difficult to evaluate due to heterogeneity of study designs including exposures, endpoints and intervening parameters measured". However, according to this expert group, the weight of evidence, both animal and human, indicates that exposure of the testes to mobile phone RF could affect sperm count, motility, concentration, and morphology, whereas evidence of impaired fertility is less robust (it is still unclear at what threshold would changes in sperm parameters occur). Mechanisms that may be involved are related to oxidative stress, which has been reported for Wi-Fi-specific exposures (78). On the other hand, SCENIHR (27) finds that the weight-of-evidence approach is not possible for male fertility due to a lack of informative studies with RF exposure.

Human data

Regarding human studies, Yildirim et al. (79) found adverse effects of wireless internet use on sperm count and mobility in patients of an infertility clinic (compared to cable internet use) and a negative correlation between daily duration of mobile phone use and sperm count. This study, however, had poorly defined exposure, as it is not clear what type of device these men used to access wireless internet (desktop computers, laptops, tablets, or mobile phones), and it appears that exposure to wireless internet was not controlled for mobile phone use and *vice versa*. Also, variability in all measured groups was large (standard deviations were equal to or larger than arithmetic means), and correlation coefficients between total sperm counts and daily duration of mobile phone use or wireless internet use were very small (Pearson's r=-0.064 and r=-0.089, respectively).

Animal and *in vitro* data

In addition to positive findings of oxidative stress in human sperm *in vitro* (72, 80) and testicular oxidative stress in rats *in vivo* evaluated by Foster and Moulder (5), there are numerous more recent *in vivo* reports (81-89) of diverse effects varying from changes in sperm count and motility to degeneration of the epididymis epithelium and necrosis of seminiferous tubules under exposure conditions varying from chronic low doses (SAR 1–4.9 mW/kg over one year) (82) to high short-term exposure (SAR 3.2 W/kg over one month) (73). Contrary to these findings, a well-described experimental study of Poulletier de Gannes et al. (65) found no adverse effects of Wi-Fi exposure on rat male and female reproductive organs, fertility or development, even at 4 W/kg applied during pregnancy and sexual maturation.

Other endpoints

Various endpoints other than brain function or male fertility were investigated in *in vivo* or *in vitro* experiments published over the last four years, and they include DNA damage in various tissues (83, 90-92), effects on heat shock proteins (93) and cellular stress (94), changes in microRNA expression (95), functional cardiovascular changes (96), oxidative stress in various tissues (89, 97, 98), development of teeth (99), female hormonal status (100), diabetes-like changes (101), changes of cornea (102) and lens (103), and adverse effects in the liver (104), kidneys (105), thyroid gland (106), thymus (93), heart myocardial cells (107), and microtubular cell structure (108).

However, many of these studies suffer from similar drawbacks as those against which Foster and Moulder warned in their review of earlier research (5), such as poorly specified Wi-Fi exposure (e.g. 87, 96, 101, 104, 107), uncertainty whether potential thermal effects have been avoided (approximately two thirds of the studies), or lack of positive controls (in almost all above cited studies). In addition, study designs rarely allowed dose-response evaluation.

Researchers who evaluate biological response to RF radiation in animal studies encounter several methodological difficulties while trying to ensure adequate exposure conditions. For example, difficulties arise when experimental animals are allowed to move freely, since exposure in such cases varies highly (20). Restraining the animals, in turn, can induce significant stress, which can seriously confound the studied outcomes (including body temperature and oxidative stress). One solution to this problem is to use a reverberation room, designed to create a diffuse or random incidence sound field. Another issue is correct measurement of exposure (real SAR values) *in vivo* and *in vitro*, since it requires expert knowledge in biology, physics, and electromagnetic theory (13, 17). Then there are some basic differences between rodents and humans that make direct extrapolation very difficult. An example is thermoregulation: while humans dissipate heat through sweating, rodents cannot do that. Another is the resonance frequency (which translates to SAR): for humans it is between 50 and 100 MHz, depending on age and electrical grounding (20), while for rats it is around 700 MHz (109). SAR also depends on body shape and orientation, which are the factors that must be taken into consideration while planning animal study (110).

Besides serious design and methodological flaws, there is a bias towards publishing only positive findings, as was pointed out in the IET 2016 report (36). For example, among the above referenced studies evaluating potential biological effects of Wi-Fi exposure, vast majority reported adverse effects. Judging by these studies, Wi-Fi exposure appears to be able to adversely affect virtually every tissue in mammals. However, bearing in mind that the output power of Wi-Fi devices is markedly below that of mobile phones and that evidence of adverse health effects of mobile phones is limited in terms of weight and scope, Wi-Fi can hardly be expected to present a greater risk than mobile phones. In fact, the IET 2016 report (36) states that it is "remarkable that four out of five experimental studies, using a wide range of both models and exposure parameters, report the detection of a biological effect". Were all of these studies reliable and robust, such adverse health effects would be common and easily reproducible in animal assays, which is not the case for the majority of outcomes.

Human studies, on the other hand, suffer from drawbacks inherent to all epidemiological studies, such as small sample size, difficult control for confounders, and various sorts of biases (e.g. selection bias, recall bias in retrospective or case-control studies, or observer bias). With Wi-Fi sources it is particularly difficult to control for concomitant RF exposure from other devices, especially those operating with different frequencies and higher output powers, such as mobile phones. While short-term, acute effects of Wi-Fi exposure can be evaluated in experimental conditions in human volunteers, assessment of long-term effects is problematic.

CONCLUSIONS

The only evidence-based biological effects of exposure to RF EMF in the frequency range of 300 kHz – 300 GHz – which includes mobile phones, mobile phone base stations, and Wi-Fi networks – are thermal effects. However, the health risks associated with temperature rise are virtually null with normal Wi-Fi use, and even with the use of a mobile phone next to the head.

As for non-thermal effects, scientific evidence is insufficient and inconsistent. Present data do not provide clear evidence of adverse effects in humans. Further research based on much more precise dosimetry procedures and protocols supported by simulations of RF field distribution inside the biological tissue is needed.

To conclude, human exposure to Wi-Fi RF fields, including exposure of children in schools, is very low and, in most cases lower than to other EMF sources in the environment. With this in mind, we, children and adults alike, should be following the practical advice to monitor and limit the use of Wi-Fi and mobile technology, as RF fields have become an unavoidable environment in and with which we have to live. There are almost no places on the Earth not covered with some of the RF fields. We have to monitor the ones which are man-made and research their possible impact on human and non-human genetic and physiological structure.

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Wi-Fi i ljudsko zdravlje

Značajan porast uporabe bežične RF komunikacije u posljednjim desetljećima te s tim povezane izloženosti ljudi umjetno stvorenom neionizirajućem zračenju (RF polja), koje prije nije postojalo na Zemlji, tema su velikog broja istraživanja mogućih utjecaja tih zračenja na okoliš i zdravlje ljudi, osobito djece i mladih, kako bi se utvrdile činjenice o međudjelovanju RF polja s genskim materijalom živih bića. U ovom radu dan je pregled aktualnih istraživanja i preporuka međunarodnih stručnih tijela. Poseban naglasak dan je na mogući utjecaj radiofrekvencijskoga zračenja na mlade odnosno na školsku djecu koja su mu tijekom školovanja svakodnevno dodatno izložena tijekom e-škole korištenjem najmodernijih Wi-Fi tehnologijskih rješenja za komunikaciju u obrazovanju.

KLJUČNE RIJEČI: e-škola; izloženost RF poljima; radiofrekvencija; SAR