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Electromagnetic Fields, Pulsed Radiofrequency Radiation, and Epigenetics: How Wireless Technologies May Affect Childhood Development

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Mobile phones and other wireless devices that produce electromagnetic fields (EMF) and pulsed radiofrequency radiation (RFR) are widely documented to cause potentially harmful health impacts that can be detrimental to young people. New epigenetic studies are profiled in this review to account for some neurodevelopmental and neurobehavioral changes due to exposure to wireless technologies. Symptoms of retarded memory, learning, cognition, attention, and behavioral problems have been reported in numerous studies and are similarly manifested in autism and attention deficit hyperactivity disorders, as a result of EMF and RFR exposures where both epigenetic drivers and genetic (DNA) damage are likely contributors. Technology benefits can be realized by adopting wired devices for education to avoid health risk and promote academic achievement.

Electromagnetic fields (EMF, including extremely low-frequency [ELF] or power frequency fields) and radiofrequency radiation (RFR) produce biologically relevant signals at very low intensity levels (Funk, Monsees, & Ozkucur, 2009; Sage, 2015; Sage & Carpenter, 2012; Sage, Hardell, & Carpenter, 2015) that have become increasingly common the everyday life of a child (Duggan, 2013; Lenhart, 2015). In today's world, nearly everyone is exposed to two types of EMFs: (a) ELF EMF from electrical and electronic appliances and power lines, and (b) RFR from wireless devices such as cell phones and cordless phones, cellular antennas and towers, and broadcast transmission towers. The term EMF is used here when referring to all EMF in general and the terms ELF or RFR when referring to the specific type of exposure. This review article profiles new evidence on the possible role of epigenetics as one cause of neurodevelopmental and neurobehavioral problems now widely seen in childhood development, including abnormal states and functional changes similar to autism and attention deficit hyperactivity disorder (ADHD), which can occur with exposure to EMF and RFR. Epigenetics refers to heritable changes in gene expression that do not involve changes to the underlying DNA sequence in response to environmental changes and have evolved to provide a more precise and stable control of gene expression and genomic regulation. Today, epigenetics equates to all information

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heritable during cell division other than by the DNA sequence. It not only provides control of gene expression but also provides means of interaction between the environment and the genome.

Several new lines of scientific evidence are synthesized to document how EMF and RFR present in wireless technologies can trigger epigenetic changes that can negatively affect childhood development, including mobile phones and Wi-Fi emissions at levels to which the fetus and young children may be exposed by use of wireless devices. Adverse health and developmental impacts in children coupled with growing reliance on mobile technologies by children, expansion of wireless educational technologies into school programs, and evidence that such technologies may hinder rather than promote academic achievement strongly suggest a reappraisal of wireless (mobile technology) applications.

Exposure and Impacts of EMF and RFR on Adults

A comprehensive review of the scientific literature indicates that chronic exposure to even very low levels can result in biological effects that can result in diminished capacity to grow and develop normal neurologic, immune, and metabolic functions, and result in serious health and learning impairments and chronic disease (Sage & Carpenter, 2012). In adults, the evidence points to increased cancer and neurodegenerative diseases (chronic degenerative and inflammatory diseases). Fertility and reproductive harm is rather consistently documented in men with damage to the DNA of sperm and deterioration of the testes (Sage & Carpenter, 2012, sections 1 and 18). Overall, the scientific evidence is suggesting that chronic exposure to wireless emissions can have detrimental effects on the fetus, infant, young child (Aldad, Gan, Gao, & Taylor, 2012; Divan, Kheifets, Obel, & Olsen, 2008, 2012), and adolescent in terms of neurological development, memory, learning, attention, concentration, behavior problems, and sleep quality (Carter, Rees, Hale, Bhattacharjee, & Paradkar, 2016). Maskey and Kim (2014) report that 835 MHz cell phone radiation exposure of very young mice can result in subsequent deficiencies in learning and language processing, disruption of brain-derived neurotrophic factor in critical windows of brain development and sensory processing, and in behavioral changes (anxiety, risk taking). Where autism spectrum conditions (ASCs) and ADHD are concerned, there is a striking similarity in effects documented from EMF/RFR exposure and those expressed in ASCs and ADHD as comprehensively reviewed in Herbert and Sage (2013a, 2013b). Mobile phone radiation exposures commonly experienced today by children wireless devices are capable of producing neurological and cognitive effects (impairments) congruent with those often exhibited in ASCs and ADHD. EMF/RFR exposures can also result in epigenetic changes in DNA expression that can impair normal functioning, without causing direct damage to DNA but simply affecting how well DNA functions are carried out (mitochondrial metabolism, production of proteins and immune cells, etc.). New epigenetic studies on mobile phone emissions support this evidence (Dasdag et al., 2015a, 2015b).

The "electronic environment" has massively changed in the last 3 decades since wireless technologies have become deeply embedded in the lives of children. Exposures relevant to children include cell and cordless phone radiation, Wi-Fi-enabled devices like wireless iPads and other wireless tablets, wireless laptops, electronic baby monitors, and surveillance devices, among other sources. Exposure levels from these sources can result in biological effects that with chronic exposure be reasonably presumed to result in adverse health harm (Sage & Carpenter, 2009, 2012). The U.S. National Toxicology Program (NTP) recently released results of the largest animal toxicity study on cancer ever performed. NTP reports a statistically significant, dose–response increased risk for malignant glioma (brain cancer) as well as precancerous lesions in male rats exposed to as low as 1.5 W/kg, below the current public safety limit, and to which children using mobile phones and wireless tablets will be exposed (Wyde et al., 2016). These results occur in the same cell types that develop cancer in human studies (Hardell, Carlberg, & Hansson Mild, 2013; Hardell & Carlberg, 2014). These brain tumor studies indicate an increased risk of deadly glioma with use of mobile phones and cordless (wireless) phones, with the highest risk for the young who use mobile phones before the age of 20 years. World Health Organization studies from 13 countries report increased brain cancer risks; and RFR was classified as a possible human carcinogen in 2011 (Baan et al., 2011; Cardis et al., 2011; Interphone Study Group, 2010, 2011).

The Kaiser Family Foundation (Rideout, Foehr, & Roberts, 2010) sets media use among 8- to 18-year-olds at more than 7.5 hr a day or 54 hr a week. Kaiser's report says too much screen time is linked to violent behavior, poor school performance, lower reading scores, sleep pattern disturbances, being overweight, and consumption of junk food. Limits on screen time are echoed by the American Academy of Pediatrics (Block, 2012). Pew

Table 1
Radiofrequency (RF) Power Density and Specific Absorption Rate (SAR) Levels Reported to Cause Tissue Damage, Changes in Health Status, Neurological Function, Cognition, and Behavior Problems

Study	RF power density ($\mu W/cm^2$)	Reported health impacts
Zwamborn et al. (2003)	0.13	Anxiety, hostility, impaired cognition
Navarro et al. (2003)	0.01–0.11	Fatigue, headaches, sleeping problems
Oberfeld et al. (2004)	0.01	Sleep and concentration disruption, fatigue and cardiovascular problems
Hutter et al. (2006)	0.05–1.0	Headache, sleep, concentration problems, other neurological problems
Thomas et al. (2008)	0.005–0.04	Headaches and concentration difficulties with short-term cell phone radiation
Kundi and Hutter (2009)	0.05–0.1	Headaches, cardiac symptoms, fatigue, sleep and concentration disruption, and other impairments
Heinrich et al. (2010)	0.003–0.02	Headache, irritation, and concentration difficulties in schoolchildren and adolescents (8–17 years old) with short-term exposure to base-station level radiofrequency radiation
Thomas et al. (2010)	0.003–0.02	Conduct and behavioral problems in schoolchildren and adolescents (8–17 years old) exposed to short-term cell phone radiation
Mohler et al. (2010)	0.005	Sleep disturbances in adults with chronic cell phone tower exposure
Buchner and Eger (2011)	0.006–0.01	Significant impact on stress hormones especially in children and chronically ill adults
Avendano et al. (2012)	0.5–1.0	Decreased sperm viability and DNA breakage in human sperm with 4 hr exposure to Wi-Fi from laptop in wireless mode
Sage and Carpenter et al. (2012)	0.00034–0.07	DNA damage, impaired sperm quality, motility, and viability from cell phones on standby mode and wireless laptop use
	SAR	
Tas et al. (2014)	0.0369 W/kg[a] 2.023 W/kg[b]	Degeneration of testes tissues with 900 MHz cell phone radiation (3 hr per day exposure for 12 months)
Atasoy et al. (2013)	0.091 W/kg[a]	Damaged DNA and reduced DNA repair at levels that comply with 802.11 g Wi-Fi public safety limits
Dasdag et al. (2015a)	0.0369 W/kg[a] 2.023 W/kg[b]	Lowered microRNA activity in brain (3 hr per day exposure for 12 months)
Akdag et al. (2016)	141.4 μW/kg[a] 7127 μW/kg[b]	DNA damage in testes by comet assay (24/7 exposure for 12 months—900 MHz cell phone radiation)
Dasdag et al. (2015b)	141.4 μW/kg[a] 7127 μW/kg[b]	Lowered microRNA activity in brain (24/7 exposure for 12 months—2.45 GHz Wi-Fi radiation)

[a]Whole body. [b]Max SAR.

Research Center (Duggan, 2013) reports 50% of cell owners download apps to their phones, 48% listen to music, video calling has tripled since 2011, and texting has massively increased in volume. Pew Research Center also reports that in teens, 58% own or have access to a tablet (wireless device). Nearly 75% of teenagers own or have access to a smartphone, and another 25%–30% have a basic cell (wireless) phone. Ninety-four percent of teens go online daily or more often. Twenty-four percent of teens report being online constantly (Lenhart, 2015).

RFR levels are associated with adverse health impacts at exposure levels common with use of wireless devices and Wi-Fi classroom installations and nearby cell towers, and have been linked to impairments in learning, memory, attention, concentration, and behavior. As shown in Table 1, the exposure levels reported to cause adverse changes in neurological function and tissue damage are much lower than current public safety limits. These exposure levels interfere with sleep and can lead to headaches, seizures, fatigue, mental confusion and burnout, immune disruption, and sperm damage. Pediatric use of wireless devices in a study of 350 very young children in urban, low-income minority populations is profiled by Kabali et al. (2015), who reported that 96.6% used mobile devices before the age of 1 year. The use of wireless devices by small children means exposure to very high levels of pulsed RFR from the wireless signals and also to the ELF EMF from the battery switching (Sage, Johansson, & Sage, 2007).

Khurana et al. (2010) reported exposure levels of 0.05–0.1 $\mu W/cm^2$ at distances < 500 m to cell towers increased risk of adverse neurobehavioral symptoms or cancer in 8 of 10 epidemiological

studies. Cell tower microwave radiation exposure on average ranges from 0.05 to 0.1 $\mu W/cm^2$, which has been shown to be associated with increased risk for neurological and sleep disorders (Hutter, Moshammer, Wallner, & Kundi, 2006). In school classrooms, or at home where wireless routers are installed, the cumulative RFR exposure from use of wireless devices, Wi-Fi, and wireless utility meters can add to cell tower exposures, so children may be exposed to 10 times or more what a cell tower delivers at several hundred meters distance.

Exposure and Impacts of EMF and RFR on Children and Adolescents

Consequences on Mental Health, Stress, and Anxiety

The exposure of the developing fetus by use of wireless devices (e.g., iPads, smartphones, and wireless laptop computers) has already raised scientific questions about what health and developmental impacts may result to the child (Aldad et al., 2012). Children born of mothers who used cell phones during pregnancy develop more behavioral problems by the time they have reached school age than children whose mothers did not use cell phones during pregnancy. Children whose mothers used cell phones during pregnancy had 25% more emotional problems, 35% more hyperactivity, 49% more conduct problems, and 34% more peer problems. The odds ratio for higher overall behavioral problems was 1.8 (1.45–2.23) in children with both prenatal and postnatal exposures to cell phones (Divan et al., 2008, 2012). Hensinger (2015) presents evidence from Germany on the negative influences of digital learning and the failure of educational technologies, particularly Wi-Fi-enabled classrooms and digital devices. He details problems of information overload, stress, and addiction factors in digital multitasking, the loss of learning abilities, student privacy and online surveillance, and wireless health effects at Wi-Fi frequencies (around 2450 MHz).

Evidence for Addictive Behavior

Roberts, Yaya, and Manolis (2014) present extensive evidence of heavy use of wireless devices and profile negative aspects of this emerging technology on students, indicating behaviors consistent with classical addiction. Paz de la Puente and Balmori (2007) note the evidence supports cell phone use to be physically addictive rather than a habituation or dependency. Henry Lai previously documented that RFR activated the endogenous opioid system of the brain, which is the part of the brain which responds to drugs, alcohol, and opioid painkillers (Lai, Carino, Horita, & Guy, 1992; Lai, Carino, & Singh, 1997; Lai, Carino, Wen, Horita, & Guy, 1991; Lai, Horita, & Guy, 1994). A significant dose–response relationship was observed between the number and duration of voice calls made on cell phones and ADHD risk among children exposed to lead in their environment (Byun et al., 2013). Addictive behavior is described in young people who have extensive use of wireless devices (Moeller, 2010; Roberts et al., 2014).

Electronic Learning and Global Decline in Academic Performance

Perhaps most important are the reported effects on learning and academic achievement. The Organisation for Economic Co-operation and Development (OECD) promotes policies that will improve the economic and social well-being of people around the world. In 2015, OECD published a 64-country report on global student achievement and technology that concluded there were no appreciable improvements in student achievement in reading, mathematics, or science in the countries that had invested heavily in information technology for education. The German Federal Ministry of Science and Research, the European Union, and the Deutsche Telecom AG provided digital notebooks (tablets) to 1,000 schoolchildren and tracked their academic performance (Schaumburg, Prasse, Tschackert, & Blomeke, 2007). They found students with notebooks had neither better grades nor better learning achievement, and tended to be less attentive.

Child Development Disruption Congruent With ASCs and ADHD

Electromagnetic radiation from chronic exposure to wireless technologies is associated with many adverse biological effects that can result in diminished capacity to grow and develop normal neurologic, immune, and metabolic functions, and result in serious health and learning impairments and chronic disease. Many of the behavioral and biological characteristics seen in autism are similar or identical to those produced by typical daily exposures to cell and cordless phone radiation, cell towers, baby monitors, wireless tablets, Wi-Fi, and other sources of pulsed electromagnetic radiation, and these are extensively profiled by Herbert and Sage (2013a, 2013b). EMF and RFR exposures appear to contribute to chronically disrupted homeostasis that is consistent with many key symptoms of autism and

impaired cognitive functioning. Critical pathways that are known to be sensitive include electrophysiology and bioenergetics of cells, neural synchrony and brainwave activity, brain inflammation, oxidative damage from free-radicals, pathological leakage of critical separations between gut–blood or blood–brain barriers, disrupted mitochondrial and immune functions, and depleted glutathione reserves. Disruption of neural synchrony by RFR exposure may be the key factor in disrupted memory and learning. Altered brainwave activity can interfere with memory formation and impair sleep, which is fundamental to memory retention. Leone et al. (2014) provide crucial data on epigenetic modulation of adult hippocampal neural stem cells with 50 Hz ELF exposure, offering both physical evidence of improved neurogenesis in the hippocampus, and a plausible (epigenetic) mechanism of action.

Epigenetics as a Plausible Biological Mechanism for EMF/RFR Effects

The study of epigenetics (the regulation of genes by environmental influences) is an appropriate tool to identify the causes of pathological changes in human embryonic and fetal development, leading to adverse developmental changes in the genome (Burgio & Migliore, 2015). The *epigenome* may be defined as a molecular and systemic network that interacts not only within itself, with its DNA, but also with the exterior world; and *epigenetics* as the study of heritable changes in gene activity that are not caused by changes in the DNA sequence. The *environment* should be considered as a *continuous flow of information* coming from outside and reaching the epigenome, causing it to activate and to continuously change its molecular and three-dimensional structure. Epigenetics gives us a critical missing dimension that shows the monumental influence the environment (meaning here the environmental exposures to EMF and RFR such as that from mobile phones and other wireless technologies) can have on how the genes are regulated and how genes express themselves in neurological development. When outside environmental signaling goes awry, impairments and diseases can occur at any age but are worse for the developing child. This is particularly damaging during fetal programming (Burgio & Migliore, 2015). The best evidence is provided by studies of histone modification, chromatin remodeling (or condensation), and microRNAs. EMF and RFR exposures studying DNA methylation, histone modification, and microRNA may be useful in the future to study epigenetics.

MicroRNA

Evidence for an epigenetic cause of damage, that is, modulation of microRNA, is presented by Dasdag et al. (2015a, 2015b) in new studies on 900 MHz cell phone radiation and 2450 MHz Wi-Fi levels of exposure. Dasdag et al. (2015b) report that very low-intensity Wi-Fi exposures over a year-long period (24 hr per day) at 141.4 μW/kg (whole body specific absorption rate [SAR]) and a maximum SAR of 7127 μW/kg lowered activity of microRNAs in the brain of adult rats. Van den Hove et al. (2014) previously reported miR-107 as epigenetically regulated miRNA linked to Alzheimer's disease and correlated with changes in neuronal development and neuronal activity.

Histone Modification

The role of histones in epigenetics revolves around how DNA chains are organized (and can be disorganized to disrupt critical biological functioning). Studies of protein folding (and misfolding) and the disabling effect of misfolded proteins on protein and enzyme expression indicate that low-intensity exposures to EMF and RFR may change protein conformation (Bohr & Bohr, 2000). Disrupting or misfolding of proteins can disrupt fundamental metabolic, growth, and cell signaling. Disruption can result from abnormal environmental signals (e.g., circadian rhythm disruption that interferes with sleep, healing, and cancer surveillance) that, in turn, disrupt how living tissues self-regulate, create overload of the system, and loss of adaptive capacity.

Chromatin Remodeling

A series of studies have reported very low-intensity microwave radiation (nonthermal) can decrease DNA repair foci (repair centers for DNA within cells) where double-strand DNA breaks would normally go for DNA repair. Inhibition of DNA repair may lead to increased risk of cancers. Belyaev, Markova, Hillert, Malmgren, and Persson (2009) suggest it is due to the inability of these damaged DNA fragments to reach DNA repair proteins because the underlying chromatin structure has been altered by microwave radiation exposure. Belyaev and Markova have provided studies reporting that microwave (RFR) exposure inhibits DNA repair (Markova, Hillert, Malmgren, Persson, & Belyaev, 2005; Belyaev et al., 2009). Microwave radiation reduces the ability of cells, in particular of human stem cells, to repair DNA damage, and

these microwave effects were observed down to 10^{-14} μW/cm^2 with 20–40 min duration to 10^{-19} μW/cm^2 at 1 hr exposure; or many thousands of times lower than wireless devices and Wi-Fi exposures produce in normal use. Poor repair of double-strand DNA breaks may lead to cancer.

Conclusion

Public health implications of wireless technologies are enormous because there has been a very rapid global deployment in homes, education, transportation, and healthcare in the last 2 decades. Even a small risk from chronic use wireless technologies may have a profound global health impact. Impacts on the fetus via parental exposures to wireless devices preconception and during in utero development, infant rearing (baby monitors, wireless surveillance, Wi-Fi routers, DECT cordless phones, etc.), and childhood preschool and academic environments all may contribute in incremental ways to a perpetually saturated habitat of wireless emissions, and health impacts from the chronic, stressful body burden of EMF and RFR.

The wide array of pathophysiological effects of EMF and RFR exposures from wireless sources do not require "the breaking of molecular bonds" as done by ionizing radiation in order for physiologically damaging effects to occur. Epigenetic mechanisms alone can change fetal development in profound ways, disrupting health by causing changes in gene activation and expression without change in gene sequences. Environmental epigenetic influences in the fetal and neonatal development (i.e., epigenetic regulation of genes rather than direct genetic effects by gene mutation) have been plausibly established to cause pathophysiological changes that can result in altered neurological development. Symptoms of neurodevelopmental problems in children like retarded memory, learning, cognition, attention, and behavioral aberrations that are similarly expressed in autism and ADHD have been reported in numerous scientific studies to occur as a result of EMF and RFR exposures, where epigenetic drivers are the most likely causes, and persistent exposures contribute to chronic dysfunction, overwhelming adaptive biological responses.

Electronic educational technologies have not resulted in better academic achievement globally and lend support to scientific studies showing adverse health and developmental impacts (OECD, 2015). Reductions in preventable exposures to EMF and RFR should be a top public health and school district priority. Technology benefits can be realized by adopting wired devices for education to avoid health risk and promote academic achievement. Wider recognition that epigenetic factors are a plausible mechanism for EMF/RFR to regulate expression of DNA and thus impact child development is a critical need. Whether future research can identify safe levels of wireless exposures is unknown, but further investigation of epigenetic markers related to EMF/RFR exposure in child development and disease is warranted.

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